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NASA

Space Station Propulsion Test Bed

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Canoga Park, California

January 1989

Prepared for
Marshall Space Flight Center
Under Contract NAS8-36418

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ABSTRACT

A test bed was fabricated under National Aeronautics and Space Administration/Marshall Space Flight Center (NASA-MSFC) Contract NAS8-36418 to demonstrate hydrogen/oxygen propulsion technology readiness for the initial operating configuration (IOC) space station application. The test bed propulsion module and computer control system were delivered in December 1985, but activation was delayed until mid-1986 while the propulsion system baseline for the station was reexamined. A new baseline was selected with hydrogen/oxygen thruster modules supplied with gas produced by electrolysis of waste water from the space shuttle and space station. As a result, an electrolysis module was designed, fabricated, and added to the test bed to provide an end-to-end simulation of the baseline system. Subsequent testing of the test bed propulsion and electrolysis modules provided an end-to-end demonstration of the complete space station propulsion system, including thruster hot firings using the oxygen and hydrogen generated from electrolysis of water. Complete autonomous control and operation of all test bed components by the microprocessor control system designed and delivered during the program was demonstrated. The technical readiness of the system is now firmly established.

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1.0 INTRODUCTION AND SUMMARY

The Space Station Propulsion Technology Program, NAS8-36418, was awarded to the Rocketdyne Division of Rockwell International in May 1985.

The objectives of this program were to (1) provide a demonstration of hydrogen/oxygen propulsion technology readiness for the IOC space station application, specifically gaseous hydrogen/oxygen and warm hydrogen thruster concepts, and (2) establish a means for evolving from the IOC space station propulsion system (SSPS) to that required to support and interface with advanced station functions. These objectives were met by performing analytical studies and by furnishing a propulsion test bed to MSFC for testing.

The program was organized into six tasks. In Task I, candidate IOC SSPS concept definition, a range of design concepts for the IOC SSPS were synthesized and evaluated. The most attractive candidates were carried into a more detailed conceptual design. In Task II, SSPS test bed design and fabrication, the propulsion test bed was designed, fabricated, and delivered to MSFC with associated test plans and documentation. A contract change to modify an existing O_2/H_2 thruster for test bed operation at a mixture ratio of 8:1 was added to this effort. In Task III, advanced SSPS concept definition, evolutionary growth concepts were to be synthesized and evaluated. In Tasks IV, V, and VI, Rocketdyne was to provide ongoing support to the test program carried out by MSFC and conduct configuration updates as needed to demonstrate evolutionary growth concepts.

The program was initiated on 24 May 1985 and proceeded on the original plan until January 1986. At that time, decisions being made on the Phase B space station program caused a change in emphasis and a funding hiatus. By January 1986 the propulsion module and microprocessor controller had been delivered to MSFC and preparation for fabricating the propellant storage module at supercritical pressures was under way.

A revised study plan was submitted in June 1986 that addressed the change in direction from using supercritical propellant storage at IOC to gaseous propellant storage and water electrolysis. The revised plan redirected remaining fabrication and test support tasks toward the water electrolysis approach. Specifically, refurbishment to a subcritical configuration was replaced with preparation, checkout, and integration of components needed to demonstrate water electrolysis, operation of main thrusters, condition monitoring, and use of waste gases with resistojets.

During August 1986 the design and fabrication of a thruster measurement system was added to the effort.

The propulsion module consisted of propellant accumulators, valving, instrumentation, and controls configured in a 9-ft cube structure designed to fit into the MSFC altitude chamber at Test Stand 300. This configuration was to simulate a basic building block structural element of the space station. This configuration permits mounting of various types of supply modules on top of the basic propulsion/accumulator module.

The microprocessor-based control system could control the entire test sequence autonomously. Sixty-four end devices could be controlled and monitored and 48 transducer data channels could be monitored for use as redlines or "go-nogo" checks. A remote terminal located at the Rocketdyne Canoga Park, California facility was connected to the system via modems so that the system software could be modified and checked whenever required. This system displayed 24 channels of reduced data updated on a one-second time basis, and data could also be displayed on the Rocketdyne remote terminal during test operations.

An electrolysis module was designed and fabricated at Rocketdyne to fit on top of the existing test bed propulsion module cube. Components tested on the module included Arde steel tanks, Structural Composites Inc. (SCI) graphite wrapped tanks, a Life Systems Inc. (LSI) electrolysis unit, and a Hamilton Standard (HSD) electrolysis unit. The module included canisters to contain

each of the water electrolysis units not designed to be operable in a vacuum. Molecular-sieve dryers designed by Boeing and fabricated at MSFC and moisture analyzers supplied by Martin were also included on the module.

The propulsion module acceptance test blowdowns were conducted in October and early November 1986. The sequence was designed to simulate thruster and resistojet firing by bleeding the gas through dump valves. Since the original design was for a 4:1 mixture ratio thruster, the acceptance tests were performed at those conditions. Successful system operation was achieved including complete autonomous operation by the stand-alone control system.

Following the acceptance test completion, the Rocketdyne 25-lbf prototype thruster (Figure 1-1) was installed in the test bed. Minor modifications were made to the test bed plumbing to run the thruster at the new design point of 8:1 mixture ratio. A series of tests were conducted on the system in December 1986, culminating with the thruster firing for 291 s, the oxygen tank maximum duration at these conditions.

After completion of design, fabrication, and delivery to MSFC of the electrolysis module components from January through June 1987, the electrolysis system testing began in early July 1987. A complete LSI 350-psia electrolysis system checkout test including operation of the dryers was performed. The LSI 350-psig electrolysis test was begun in late July. The tests were terminated when system pressures dropped sharply, indicating leakage in the gaseous hydrogen system. Subsequent checks revealed a malfunction in the electrolysis unit caused by erroneous pressures applied to purge points. The test was considered a qualified success in that gas was produced and delivered to the storage tanks at up to 160 psig under automatic control prior to the malfunction. The LSI unit was damaged by the error and removed for repairs.

The HSD 1,000-psi electrolysis unit checkout test was successfully conducted in late October 1987. The test series was started on November 16 and was completed successfully with a 175 s firing of the 25-lbf thruster on December 1 using the gases generated by the electrolysis unit.

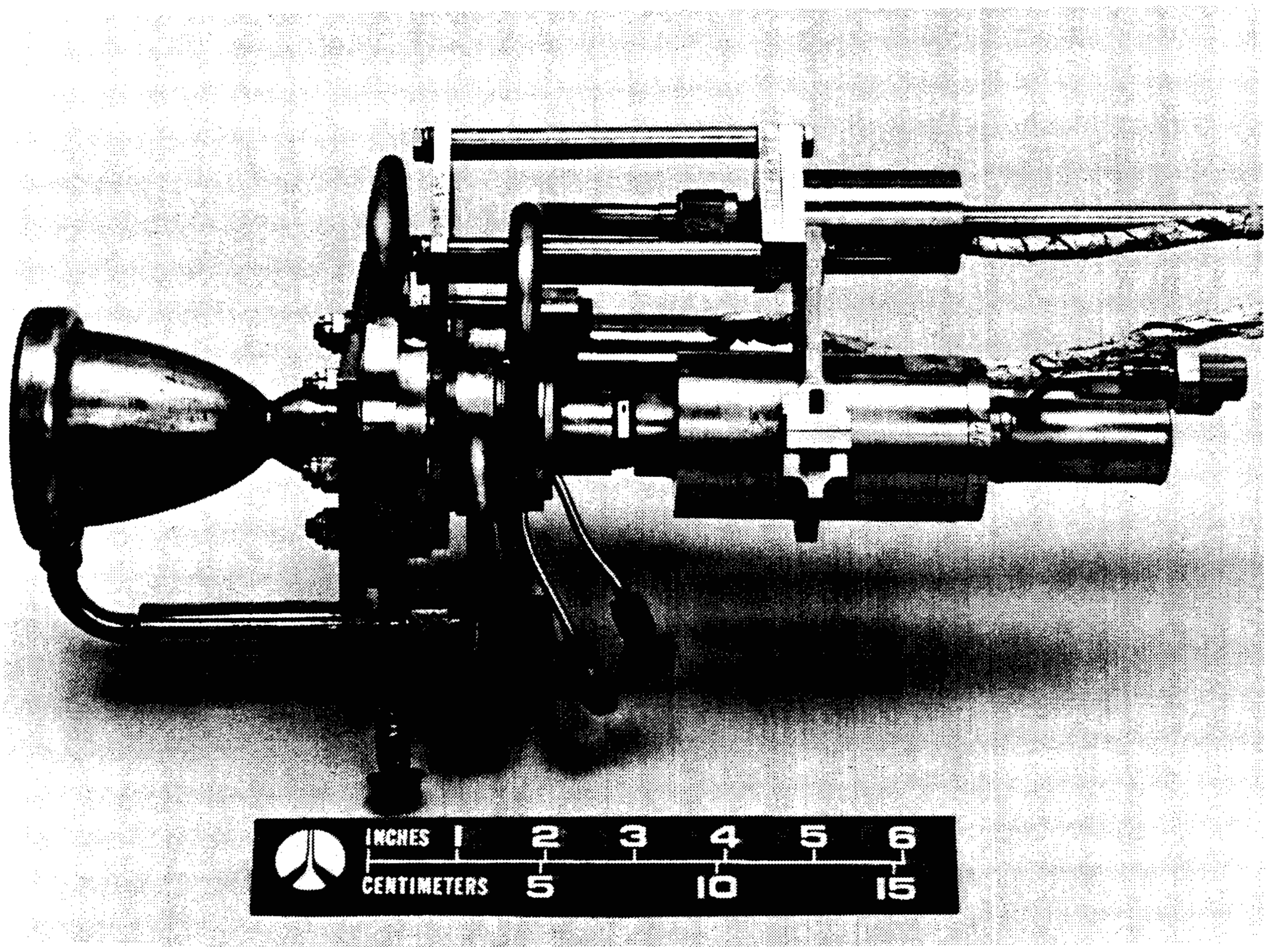

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Figure 1-1. Rocketdyne Prototype 8:1 Thruster

Prior to and following completion of the HSD electrolysis tests, tests were conducted on flight-type thrusters representing updated versions of the prototype thruster. These thrusters were fabricated by Rocketdyne for NASA Lewis Research Center (LeRC) and the program is detailed in Reference 1. Up to 14 tests per day were routinely performed simulating multiple firings of the system. Tests of advanced system and igniter designs were also conducted.

A total of 186 tests were conducted with the space station propulsion test bed from October 1986 through March 1988. The tests evaluated the test bed propulsion module (including the gas accumulator system), the water electrolysis

system, the 25-lbf thruster, and the ignition system. Advanced injector and ignition system designs were also tested. The integrated microprocessor computer controller was used throughout to command, control and monitor all the tests. A summary of all tests performed on the test bed is presented in Appendix B.

Following completion of the thruster tests, the test bed was removed from the vacuum chamber and stored.

The tests provided an evaluation of a simulated SSPS with all major hardware components and control systems represented. Test data are directly applicable to the future design and development of the flight propulsion system. Successful operation of the end-to-end SSPS was demonstrated.

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2.0 PROPULSION CONCEPT DEFINITION

The program's initial task objective was defining the propulsion system concept for the flight configuration to guide test bed design and testing. As illustrated in Figure 2-1, this study assumed the reference power tower space station configuration and the reference four location propulsion system. The electrical power system was assumed to incorporate eight planar silicon photovoltaic arrays. A 250-nmi station assembly and resupply altitude was used with a reference 2σ density atmosphere.

The SSPS functions included velocity corrections and attitude control. The velocity correction requirements consisted of atmospheric drag makeup (reboost), debris avoidance, and reserves. The attitude control requirements included reboost at attitude control, torques exceeding control moment gyro (CMG) capacity, CMG backup, and CMG desaturation.

- **ARCHITECTURE**
  - **MASS**
  - **SIZE**
  - **SHAPE**
- **PERFORMANCE**
  - **ATTITUDE CONTROL**
  - **VELOCITY CONTROL**
- **OPERATIONS**
  - **SAFETY**
  - **MAINTENANCE**
  - **CUSTOMER ACCOMMODATIONS**
  - **CREW ACTIVITIES**
- **SYSTEM INTERFACE**
  - **GNC**
  - **EC/LSS**
  - **OTHERS**
- **EVOLUTION AND OPPORTUNITY**
  - **CUSTOMER NEEDS**
  - **ADDITIONAL FACILITIES**
  - **UTILITY SERVICE ($O_2/H_2/H_2O$)**

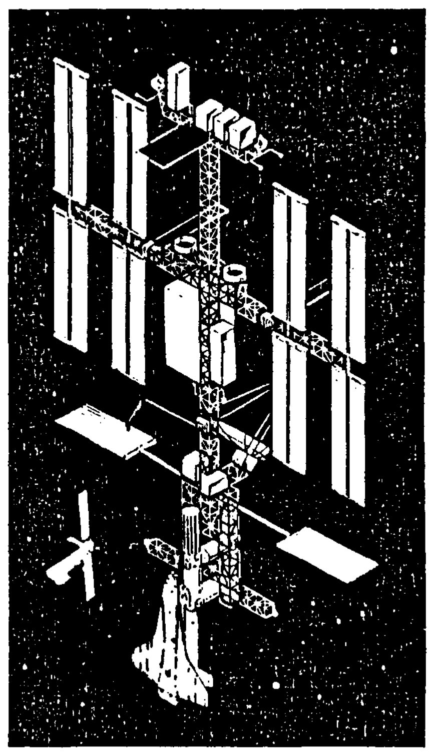

Figure 2-1. Scope of Requirements Considered

As shown in Figure 2-1, the SSPS requirements evaluated considered the station architecture, propulsion system performance, SSPS operations, interfaces, and SSPS evolution and opportunity. Each of the velocity correction and attitude control requirements were evaluated to determine their impact on the SSPS, the design basis, and the design selection sensitivity to baseline change.

The station safety requirements specify a fail-operational/fail-safe/restorable system with designed-in safety. The latter would include damage containment. The customer accommodation requires a micro-gravity ($<10^{-5}$g) and contamination-limited environment. The processing and operations requirements include the need to access, service, and maintain the SSPS and the SSPS is to be launched in the Space Transportation System (STS). System maintenance and servicing requirements consist of: (1) easy replacement at lowest orbital replacement unit (ORU), (2) condition-monitoring fault detection, and (3) propellant resupply servicing.

For this study task, two different impulse requirements were evaluated (Table 2-1). The total 90-day impulse values were similar for the two impulse requirements. For the reference impulse, the reboost impulse is approximately one-third of the total impulse (two-thirds contingency). In the reboost committee impulse, the reboost impulse is approximately three-fourths of the total impulse.

During the conduct of this task, the dual keel station configuration (Figure 2-2) was introduced. The resulting changes in impulse values were not defined.

2.1 SYSTEM EVALUATION

The system evaluation of the oxygen/hydrogen SSPS involved: (1) the synthesis of potential candidate systems and preliminary screening, (2) the development of a selection methodology with the establishment of selection criteria and their relative importance, and (3) the evaluation of the candidate systems to define comparative data for each selection criteria.

Table 2-1. IOC Impulse Design Requirements
(2 sigma atmosphere)

	90-day Impulse, lbf-s			
	Reference	10-year Average	Proposed Reboost Committee (8 July 1985)	10-year Average
• Reboost and other resupplied propellants				
• Reboost (drag makeup)	483,000	224,000	854,000	400,000
• Orbit makeup attitude control	--	(Resistojet)	221,000	100,000
• Momentum management	--		57,000	
• Transients				
• Orbiter berthing	26,000	26,000	26,000	150,000
• Other	--	(Thruster)	66,000	
Subtotal (resupplied propellants)	509,000	250,000	1,224,000	650,000
• Contingency				
• Collision avoidance (ΔV = 5 fps)	61,500		70,000	
• Altitude transfer (20 nmi)	831,000		--	
• Attitude control backup - CMGs	147,000		269,000	
• CMG repair	--		11,000	
• Reserve (10% of reboost)	--		85,000	
Subtotal (stored propellants)	1,039,500		435,000	
• Total impulse	1,548,500		1,659,000	

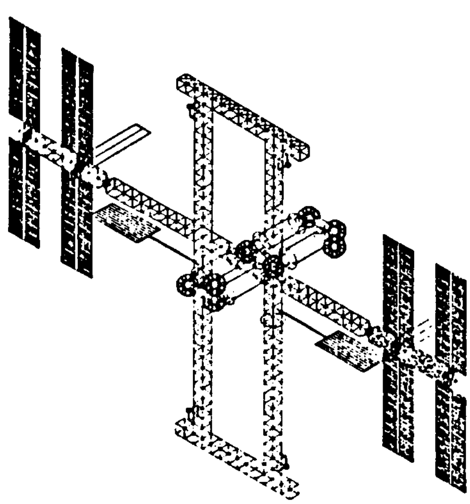

Figure 2-2. Dual Keel Configuration

2.1.1 System Synthesis

The major emphasis in synthesizing candidate O_2 and H_2 based propulsion systems to be evaluated was to strive for system simplicity. Candidate systems incorporating pumps, turbines, or gas generators were eliminated because of their increased system complexity. To maintain the propellant storage volume and meet minimum required thruster inlet temperatures (200°R for H_2 and 400°R for O_2), propellant thermal conditioning is required. One attractive approach to propellant tank pressurization is through heat addition. Electrical power would supply the energy required for tank pressurization and propellant thermal conditioning. On-line gas generation (real time during thruster firing) would require excessive power to provide the full thruster flow rate. To minimize power requirements, accumulators are required to decouple the tank pressurization and thermal conditioning from the thruster operation. Accumulators are also required for water electrolysis approaches for the same reason.

An initial screening of the candidate systems assessed system complexity, system volume, and energy requirements. This resulted in the eight candidate systems presented in Table 2-2. These include O_2/H_2 and warm H_2 systems with and without H_2 resistojets and integrated with the environmental control and life-support system (ECLSS), a O_2/H_2 system with dedicated water electrolysis, and a combined warm H_2 attitude control system (ACS) with an O_2/H_2 drag makeup system. Sample schematics of these candidate systems are presented in Figure 2-3.

The propellants and their origin, the type of thruster, and whether the candidate system would be used for drag makeup (low or high thrust) and/or attitude control (high thrust) are summarized pictorially in Figure 2-4 for all candidate systems.

Table 2-2. IOC SSPS Candidate Systems

1	Oxygen/hydrogen
2	Warm hydrogen
3	Oxygen/hydrogen + hydrogen resistojet
4	Warm hydrogen + hydrogen resistojet
5	Oxygen/hydrogen from water electrolysis
6	Oxygen/hydrogen integrated with ECLSS
	• with CO_2 resistojets
	• with CH_4 resistojets
7	Warm hydrogen integrated with ECLSS
	• with CO_2 resistojets
	• with CH_4 resistojets
8	Combined alternate
	• Warm hydrogen ACS with oxygen/hydrogen drag makeup

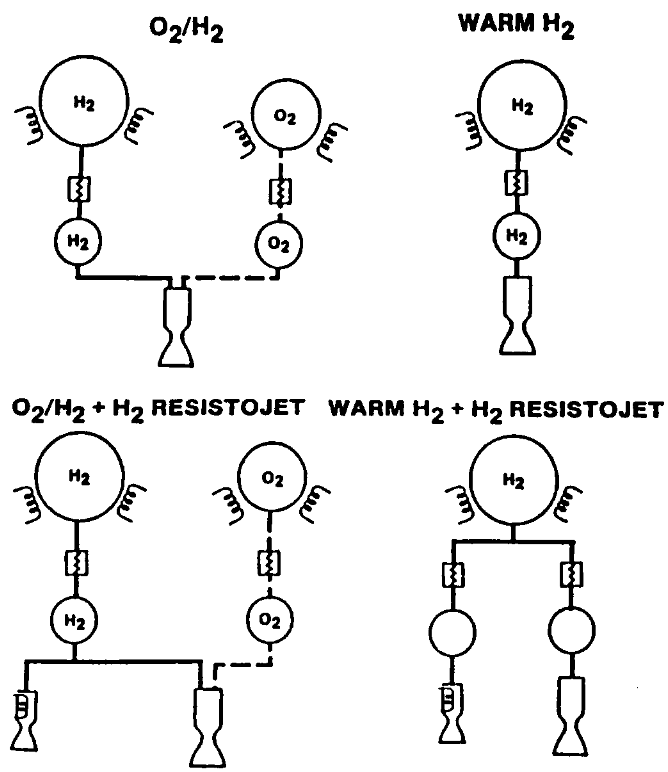

Figure 2-3. SSPS Candidates (Sheet 1 of 2)

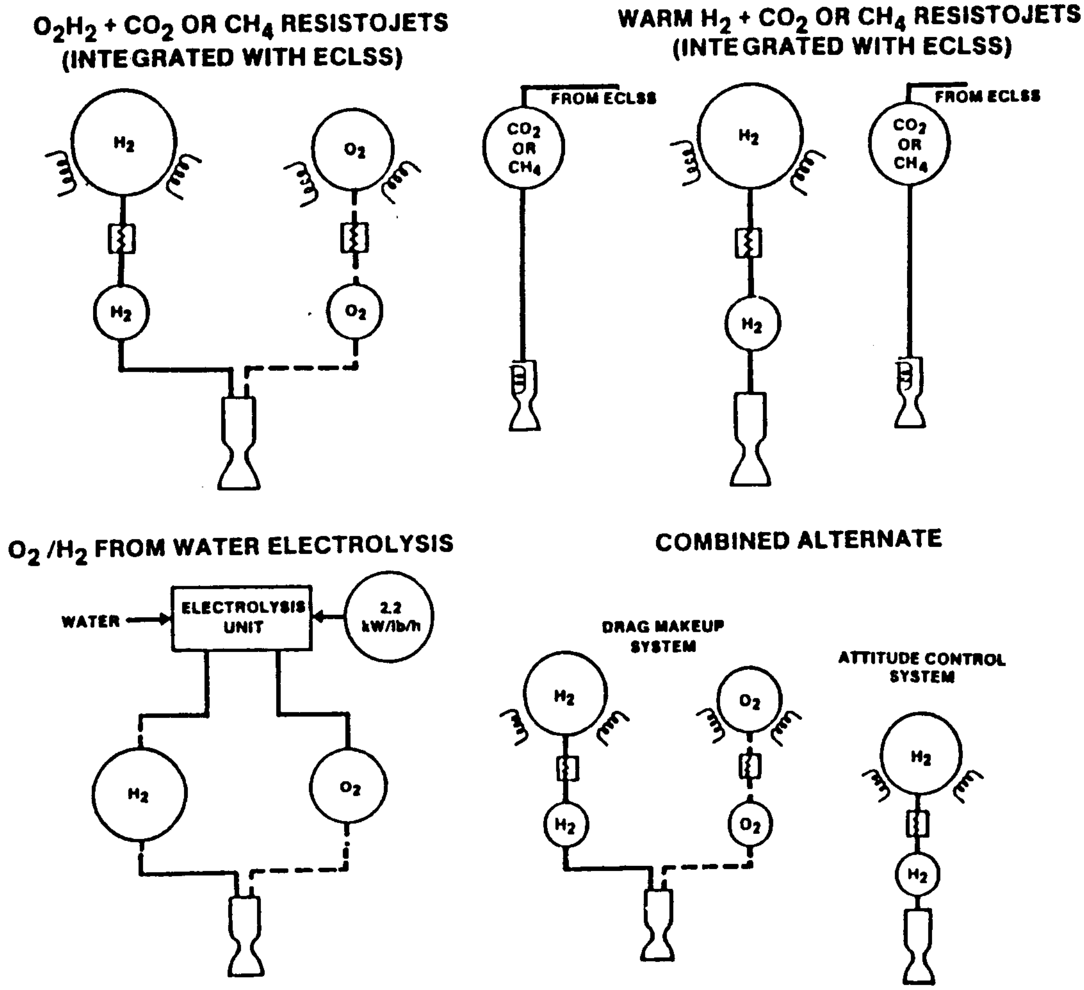

Figure 2-3. SSPS Candidates (Sheet 2 of 2)

2.1.2 Evaluation

The eight SSPS candidates were evaluated in sufficient depth for each evaluation criterion to discriminate between the different systems. Detailed system schematics were prepared defining the component arrangement, component type, and redundancy. The overall and resupply system weight, volume, and energy requirements were determined. The assumptions and ground rules used in this evaluation are shown in Table 2-3.

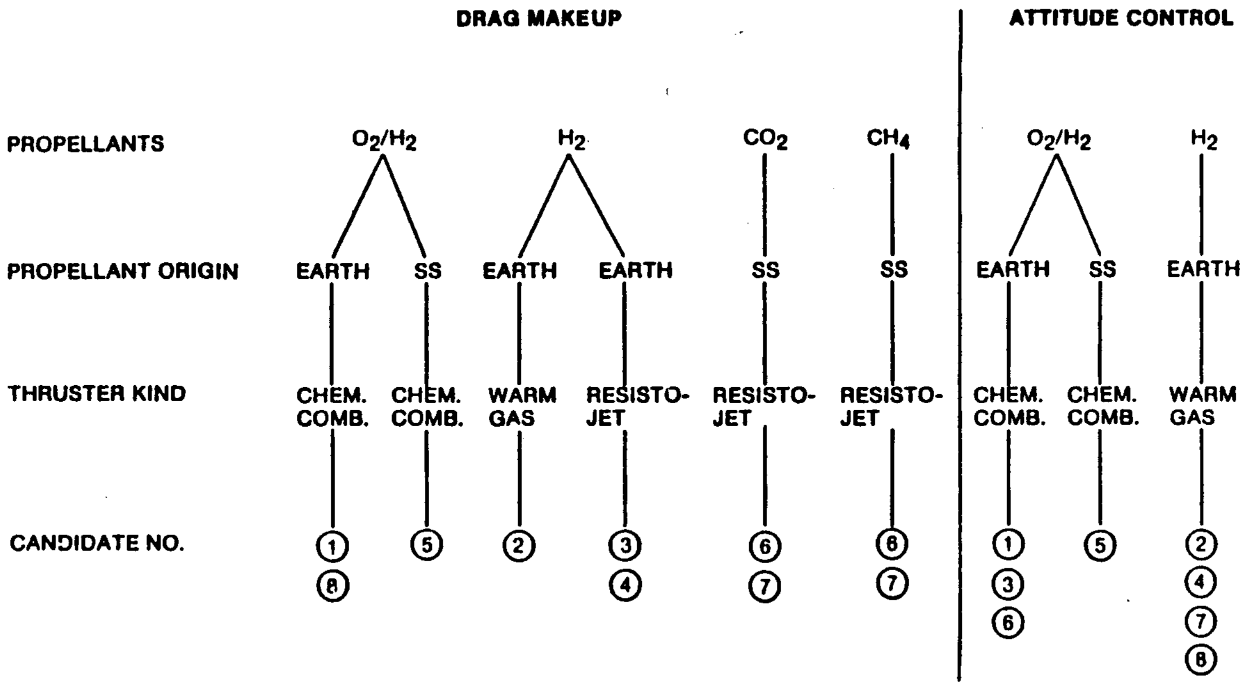

Figure 2-4. SSPS Candidate Concepts

Table 2-3. Assumptions and Ground Rules

- Supercritical storage for IOC station
- Centralized propellant storage and thermal conditioning with modular accumulators
- Thermal conditioning of propellant by electrical heater with larger thermal inertia
- Accumulators operate in blowdown mode (no heat added during blowdown)
- Nominal mixture ratio of 4:1 ±1 for oxygen/hydrogen bipropellant (except electrolysis at 8:1)
- System supplies propellant to four 25-lbf thrusters, possibly also resistojets
- Long-duration hardware soak temperature will reach ~600°R
- Minimum thruster inlet temperatures: 200°R (hydrogen), 400°R (oxygen)
- Maximum tank diameter is 9 ft (cube dimension)
- Specific impulse values
  - Oxygen/hydrogen — 440 (380 at 8:1)
  - Warm hydrogen — 270
  - Hydrogen resistojet — 500
  - CO_2 — 130
  - CH_4 — 160
- Maximum available power — 10% of total station power

2.1.3 Selection Methodology

To ensure an objective candidate selection, a structured evaluation and selection methodology was used. The overall selection process is schematically illustrated in Figure 2-5 and involves the generation and compilation of data pertinent to specific evaluation criteria which are quantified to a numerical rating. The steps involved in this procedure are presented in Table 2-4.

As shown in Table 2-4, the selection criteria to be used were first developed. This was accomplished through a review of the SSPS requirements identifying critical areas of concern and through interaction with NASA-MSFC personnel. Table 2-5 presents the seven selection criteria defined for the SSPS

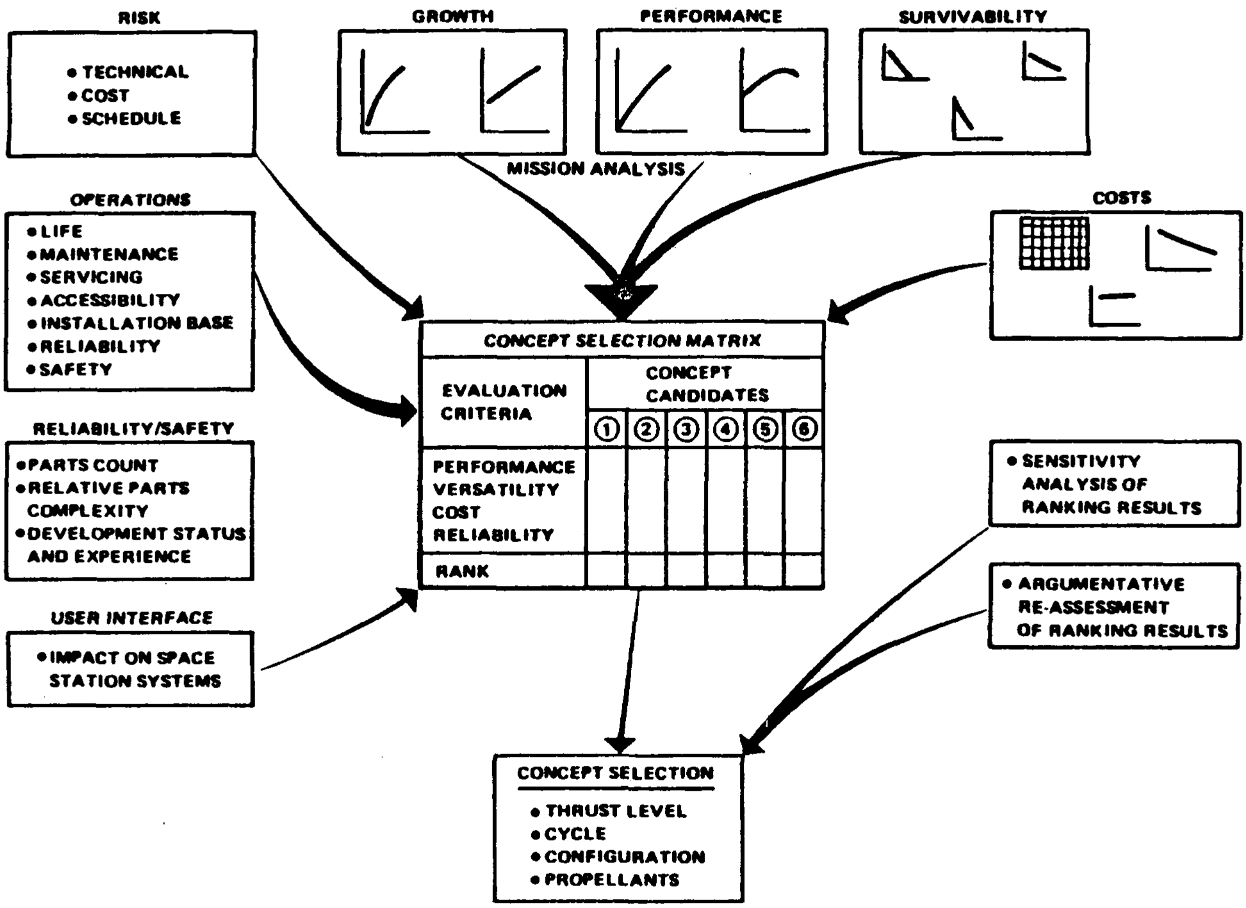

Figure 2-5. Concept Selection Process

Table 2-4. Concept Selection Approach

- Develop selection criteria
- Establish weighting factors for selection criteria
- Establish normalized figures of merit for criteria ratings
- Rate propulsion system concepts
- Multiply ratings with weighting factors
- Sum products for each propulsion system concept
- Rank propulsion systems concepts according to magnitude of product sums
- Determine rating sensitivities
- Review and reassess ranking results

Table 2-5. SSPS Selection

- **Reliability and Safety**
  - **Simplicity of Concept**
  - **Number of Components**
  - **Number/Severity of Potential Safety Hazards**
  - **Operating Procedure Complexity**
  - **Number of Life/MTBF Limiting Components**
- **Contamination Potential**
  - **Exhaust Plume Impingement**
  - **Effluent Contamination Potential**
  - **Plume Radiation and Optical Effects**
- **Technical Risk**
  - **Technology Readiness**
  - **Technology Uncertainty**
  - **Sensitivity to Space Station Configuration**
- **IOC and Life Cycle Cost**
  - **IOC (Phase C/D) Cost**
  - **Life Cycle Cost**
- **Growth Potential**
  - **Ease of Modular Upgrading**
  - **Cost of Scarring for Growth**
  - **Integration with Growth Space Station**
- **Operational Utility**
  - **Launch Packaging**
  - **Ease of Deployment**
  - **Refueling Mode**
  - **Ease of Repair/Restoration**
- **Potential SSPE Integration**
  - **Propulsion System Energy Requirement**
  - **Interaction With Other Space Station Subsystems**

and the specific items influencing each criterion (subcriteria). The criteria included reliability and safety, contamination potential, technical risk, IOC and life cycle cost (LCC), growth potential, operational utility, and potential space station program element (SSPE) integration.

Relative weighting factors were determined by establishing the relative importance of each criterion. A total of 19 technical experts were surveyed. Through the use of Rocketdyne's Analytical Hierarchy Process (AHP) computer code, the survey results were quantified (Figure 2-6). Reliability and safety was the most important criterion, followed by contamination and technical risk. IOC and LCC was the fourth highest criteria. The SSPE integration criteria were the least important criteria.

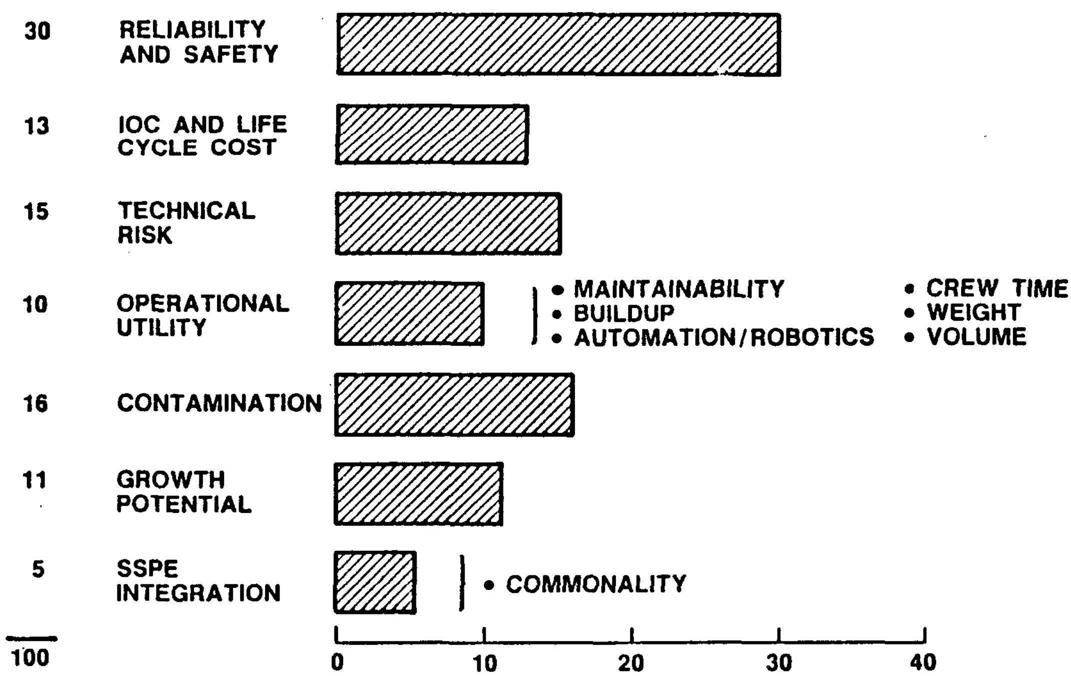

Figure 2-6. Selection Criteria Weighting Factors

Next, a preliminary point design of each candidate system was established and data generated to enable a numerical rating for each criterion. Each criterion ranking is multiplied by the corresponding weighting factor to obtain a weighted rating. This is performed for each criterion for each candidate system. The sum of the weighted ratings for a candidate system is the overall rating. The candidate systems are then ranked according to the numerical value of the overall rating. The sensitivity of the weighting factors is determined by performing the same process with all the criteria weighting factors equal. Finally, the ranking of the candidate systems is reviewed and assessed and used to support the chosen candidate systems for recommendation.

A detailed schematic was prepared for each candidate system based on the simple candidate system schematics (Figure 2-3), the fail-operational/fail-safe requirement, and the utilization of operational maintainability. As a representative sample, the detailed schematics of the O_2/H_2 and the warm H_2 candidate system are presented in Figures 2-7 and 2-8. In these figures major components, valves, regulators, and quick disconnects are shown, as well as the component redundancy. The propellant supply was divided into three modules. For the reference total impulse, one module was the 90-day supply and the other two modules were the contingency propellant. Propellant supply tank pressurization was provided by electrical heating. All propellant tanks are pressurized to a point above their respective critical pressure (supercritical pressure). Heat exchangers were used to condition the propellant in the accumulator.

To provide data for the evaluation of the different candidate systems, the total system weight and volume were determined using the preliminary system design computer code. This computer code can design up to 28 different candidate systems with its variable schematic capability. Propellant flows, pressures, temperature, and component weights and volumes are determined. The system volume is computed and consisted of resupply and contingency propellant tanks, and the accumulators. Also, the total system weight is calculated and includes the propellant (90-day plus contingency) and all other components

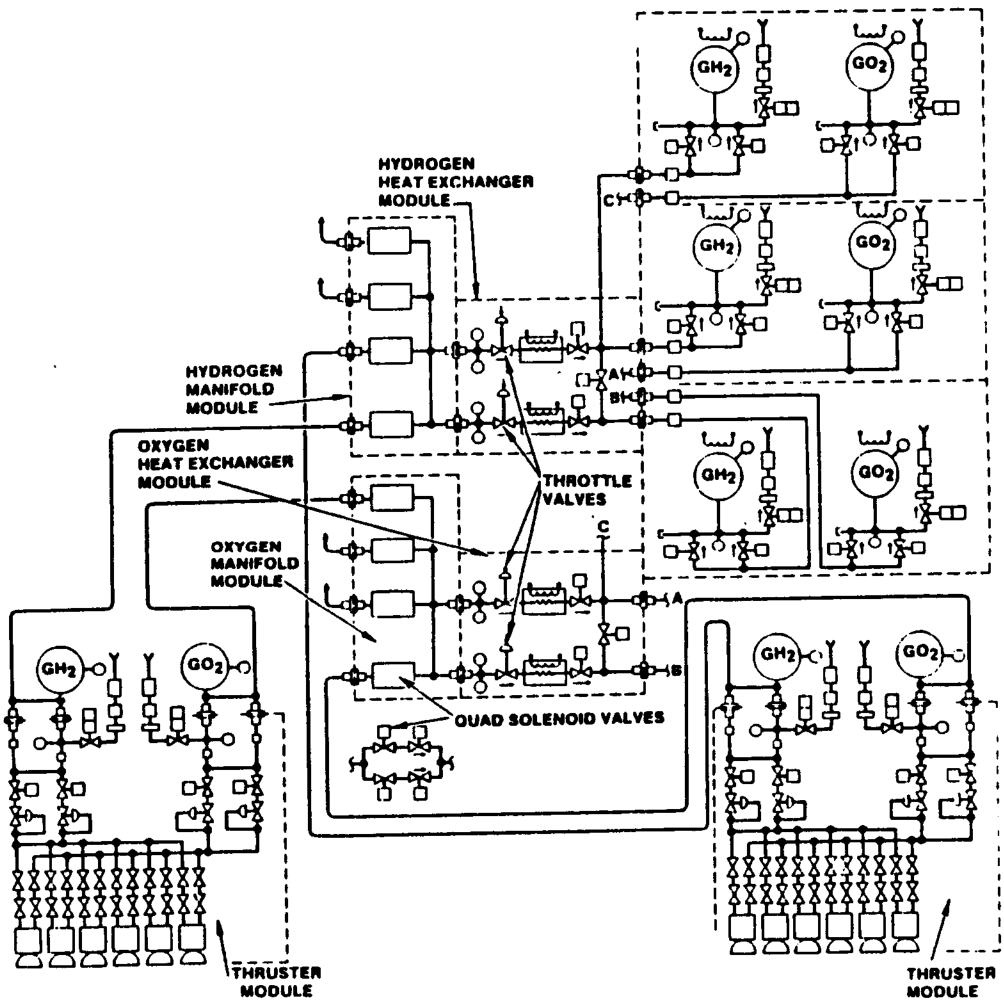

Figure 2-7. O_2/H_2 System

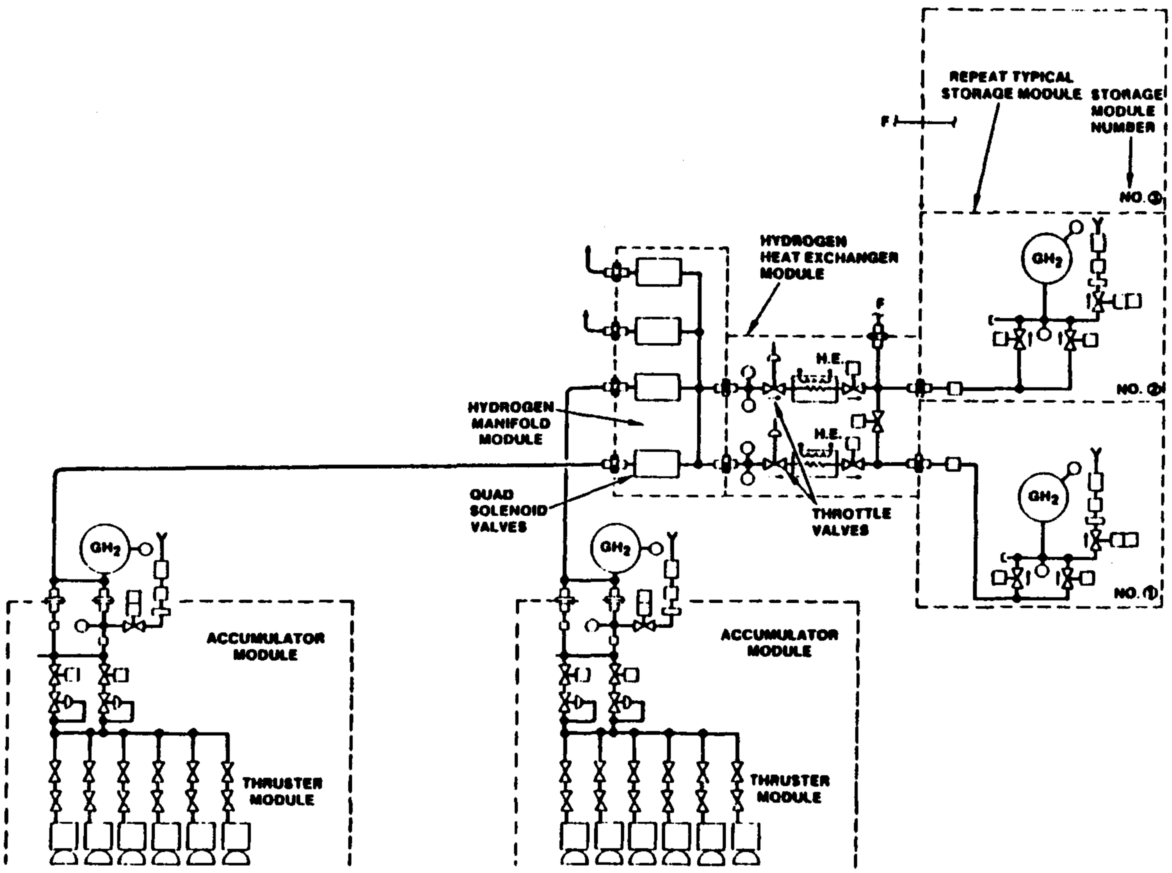

Figure 2-8. Warm H_2 System

(tanks, lines, valves, heat exchangers, accumulators, pressure regulators, quick disconnects, and instrumentation). The resupply weight consisted of the 90-day resupplied propellant, tanks, instrumentation, and associated plumbing.

A study was conducted to determine the appropriate object function for system optimization. Factors such as initial cost (volume/weight), resupply cost (resupply weight), and a combination of these were examined. Minimization of total weight provided a system close to minimum IOC cost and resupply cost with reasonable volume. Each candidate system was designed for each of the two total impulses and optimized for minimum total wet system weight. Total system weight will directly influence the production and initial launch cost, and the resupply weight will impact the operational costs. Propellant tank pressure, accumulator size, accumulator pressure and temperature range, and

thruster chamber pressure were varied internal to the computer code to obtain a minimum system wet weight.

In addition to total impulses previously presented in Table 2-1 and the overall assumptions in Table 2-3, the detailed assumptions used in this evaluation are shown in Table 2-6. Preliminary designs were obtained for each of the eight candidate systems. The general trends in the optimization included lower chamber pressures and increases in area ratio. Lower pressures were

Table 2-6. System Evaluating Assumptions

• Supercritical Propellant Storage Except for Water Electrolysis		
• Tank and Accumulator Material		
• Fuel Tank and Accumulator	Aluminum 2219-T62	
• Oxidizer Tank and Accumulator	Inconel 718	
• ECLSS Influenced Impulses		
• CO_2 Resistojet		
• Total Available Impulse	154,440 lb-sec	
• Specific Impulse	130 lbf-sec/lbm	
• Number of Tank Charges	3	
• CH_4 Resistojet		
• Total Available Impulse	69,120 lb-sec	
• Specific Impulse	160 lbf-sec/lbm	
• Number of Tank Charges	3	
• Combined Alternate System Impulse	Reference	Proposed
• Drag Makeup (Oxygen/Hydrogen)		
• 90 Days, lb-sec	483,000	854,000
• Contingency, lb-sec	892,000	155,000
• Attitude Control (Warm H_2)		
• 90 days, lb-sec	26,000	370,000
• Contingency, lb-sec	147,000	280,000
• Oxygen/Hydrogen System		
• Mixture Ratio	4 to 1	
• Minimum Thruster Inlet Temp.		
• Hydrogen	200 R	
• Oxygen	400 R	
• Water Electrolysis System		
• Mixture Ratio (Oxygen/Hydrogen)	8 to 1	
• Tank Design Temperature	500 R	
• Tank Design Pressure	3000 psia	

desirable to reduce the propellant tank and accumulator weights, but pressures were maintained above the respective fuel and oxidizer critical pressures. The resulting normalized total system (O_2/H_2 system chosen as the reference) and resupply weight and volume are presented in Figures 2-9 through 2-12. The O_2/H_2 system resulted in the lowest total system and resupply weight and volume. The O_2/H_2 system integrated with the ECLSS using CO_2 resistojets resulted in a lower resupply volume because of the utilization of on-board CO_2. The O_2/H_2 system with water electrolysis resulted in the highest total system weight. Because immediately after the initial station deployment, this candidate system cannot provide sufficient propellant for reboost, propellant and high-pressure tanks were incorporated in the system to provide for the initial station reboost. Subsequently, the propellants are generated and stored. The warm H_2 system has the highest total system and resupply volume and the highest resupply weight.

The total energy required (propellant tank pressurization, propellant thermal conditioning, resistojet power, and water electrolysis power) for each of the candidate systems is presented in Figure 2-13. The crosshatched portion of each bar represents the energy required to pressurize the propellant tanks for expulsion and thermally condition the propellants. The open portion of the bar is either the energy required for resistojets or for water electrolysis. The O_2/H_2 system resulted in the lowest total energy requirement. The water electrolysis system had the highest total energy requirement because of the energy required for electrolysis, although the peak power was low.

In the following sections, each candidate system is evaluated and compared with respect to each of the seven selection criteria.

2.1.3.1 Reliability/Safety. The assessment of the reliability of each candidate system involved the determination of the total number of components (both active and passive), the total number of active components, and total number of active components with limited life. In general, system complexity and unreliability will increase with the total number of components and with the

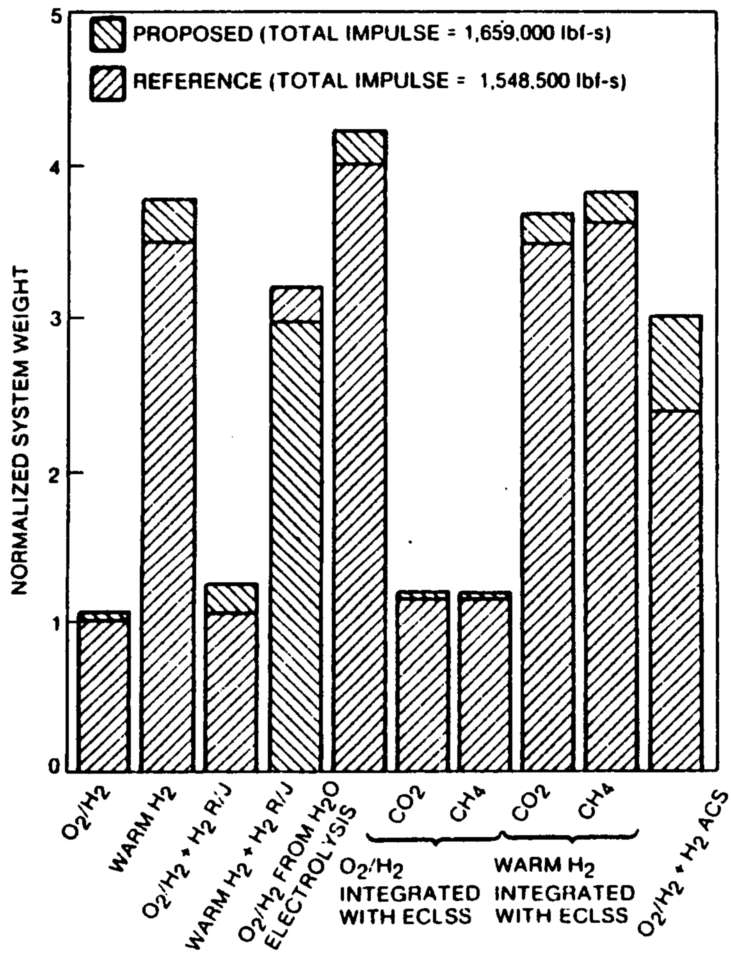

Figure 2-9. Normalized Weight Comparison of System Candidates (90 Days and Contingency)

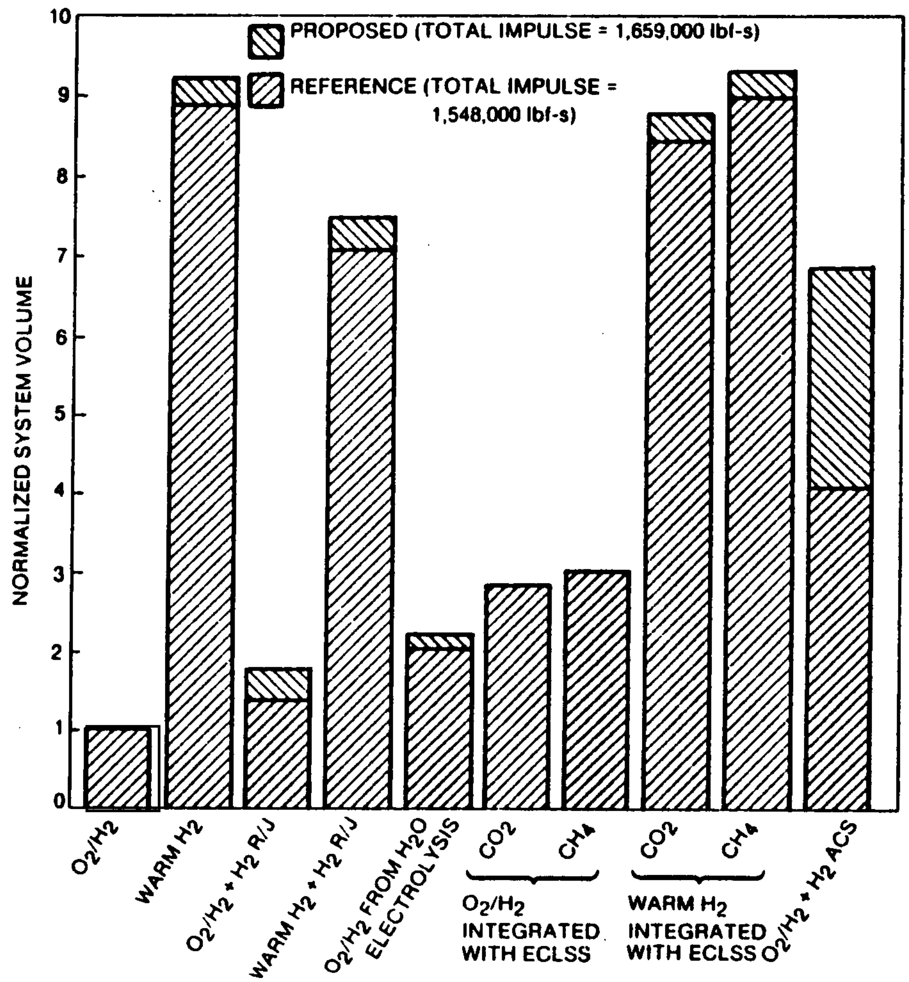

Figure 2-10. Normalized Volume Comparison of System Candidates (90 Days and Contingency)

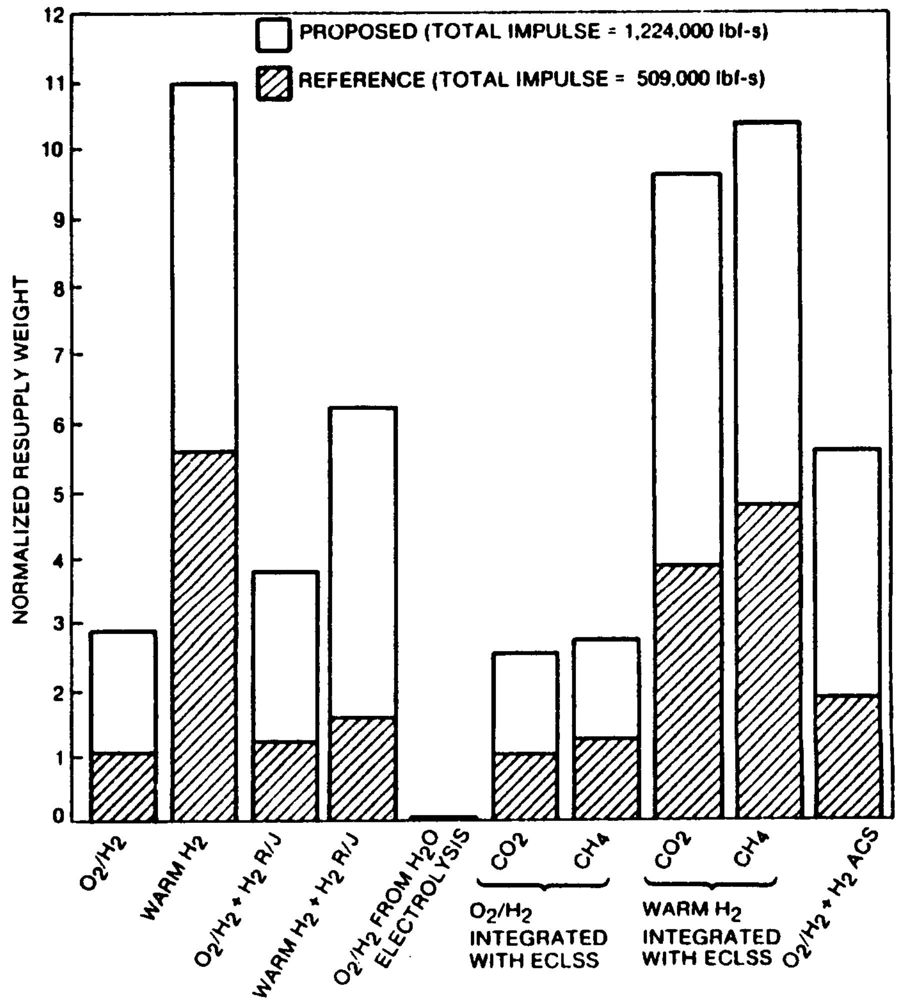

Figure 2-11. Normalized Resupply Weight Comparison of System Candidates

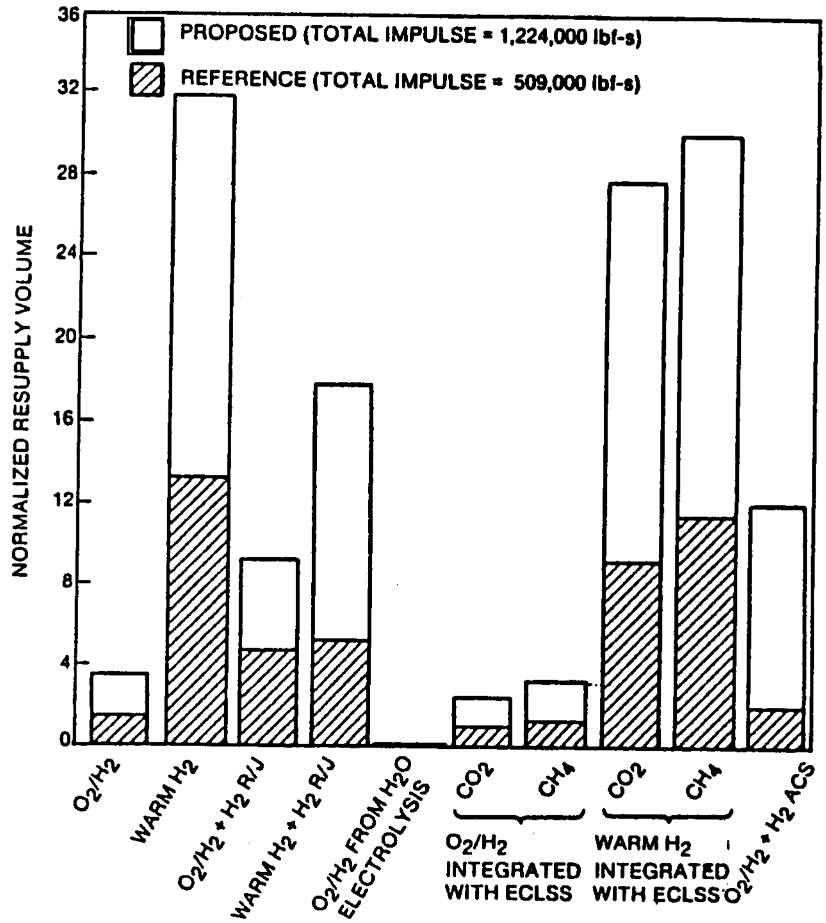

Figure 2-12. Normalized Resupply Volume Comparison of System Candidates

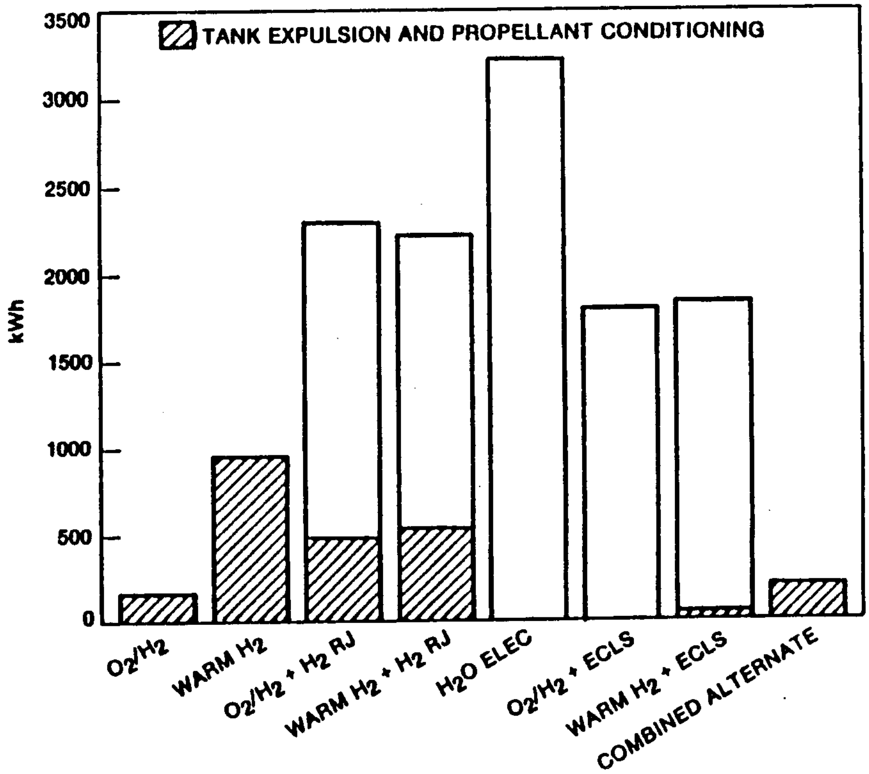

Figure 2-13. Total Energy Comparison

total number of active components. As shown in Table 2-7, the warm H_2 system contained the lowest number of components and the O_2/H_2 system integrated with the ECLSS contained the largest number of components. Similarly, when the number of active components were considered (Table 2-7), the warm H_2 system resulted in the lowest number. The O_2/H_2 system with the H_2 resistojet had the largest number of active components. As expected, the systems using only hydrogen had less total components and less active components than the O_2/H_2 systems.

Also, the system reliability is related to the use time divided by the mean time between failure (MTBF). Again, as shown in Table 2-8, the warm H_2 system had the lowest number of active components with limited life (higher reliability rating) and the O_2/H_2 system integrated with the ECLSS had the largest number.

Table 2-7. Component Count

Candidate System	Total Number of Components (Active and Standby)	Total Number of Active Components
1 O_2/H_2	215	128
2 Warm H_2	119	76
3 O_2/H_2 + H_2 Resistojet	230	175
4 Warm H_2 + H_2 Resistojet	157	89
5 O_2/H_2 From Electrolysis	132 (plus electrolysis)	79 (plus electrolysis)
6 O_2/H_2 With ECLSS	272	156
7 H_2 With ECLSS	171	97
8 Warm H_2 ACS + O_2/H_2 Reboost	188	114

A general overall reliability assessment was that the candidate systems containing only hydrogen had a higher reliability rating than candidates incorporating oxygen and hydrogen.

The safety assessment identified potential major safety hazards and their corresponding inhibitors. The potential safety hazards identified were overheating of the oxygen tanks and oxygen heat exchangers and overpressurization of the propellant tanks. The occurrence of these failures are believed to be highly unlikely with the controls envisioned to monitor the system operation and the hardware condition. Inhibitors to minimize the potential of these hazards were primarily associated with design provisions (e.g., relief valves, leak-before-burst criteria, and large safety factors), instrumentation, redundant controls, and the hardware health-monitoring system.

Therefore, in general, the candidate systems which use only hydrogen resulted in a higher reliability and safety rating than the systems using oxygen and hydrogen.

Table 2-8. Number of Active Components With Potentially Limited Life/MTBF

Space Station Propulsion System Candidate	A Oxygen Tank Heaters	B Thrusters	C Regulators Throttle Valves	D Oxygen Heat Exchangers	E Latching Valves	F Automatic QDs	G Electrolysis Units	A through G Total	A + D + F Components With High MTBF
1. Oxygen/Hydrogen	1	24	10	1	38	6	–	81	8
2. Warm Hydrogen	–	24	5	–	19	3	–	51	3
3. Oxygen/Hydrogen + Hydrogen Resistojet	1	24	14	1	40	6	–	86	8
4. Warm Hydrogen + Hydrogen Resistojet	–	24	9	–	19	3	–	55	3
5. Oxygen/Hydrogen from Electrolysis	–	24	8	–	31	1	2	63 (plus 2 electrolysis)	2 electrolysis
6. Oxygen/Hydrogen with ECLSS	1	32	14	1	48	6	–	102	8
7. Hydrogen with ECLSS	–	32	9	–	29	3	–	73	3
8. Warm Hydrogen ACS + Oxygen/Hydrogen Reboost	1	28	8	1	30	6	–	74	8

2.1.3.2 Contamination Potential. External contamination requirements stipulate limits on molecular column densities, background light levels, particle releases and deposits of matter generated on the station during overall quiescent operation of the space station. Many optical payloads on the station are sensitive to nontransparent gases made up of molecules or particles which absorb in the visible, infrared or ultraviolet parts of the spectrum. Telescopes and related equipment must avoid deposits of condensed materials on their mirrors. Electromagnetic contamination in the form of electric and magnetic fields can also affect susceptible sensors.

Figure 2-14 shows the sources contributing to the total external contamination environment, the SSPS being just one source of many. The most significant releases are from the docking of the Space Shuttle Orbiter on station resupply trips. Also, the atmospheric atomic oxygen prevalent at low Earth orbit (LEO) is quite severe on material surfaces. An important factor in minimizing contamination effects caused by the propulsion system is the proper scheduling of

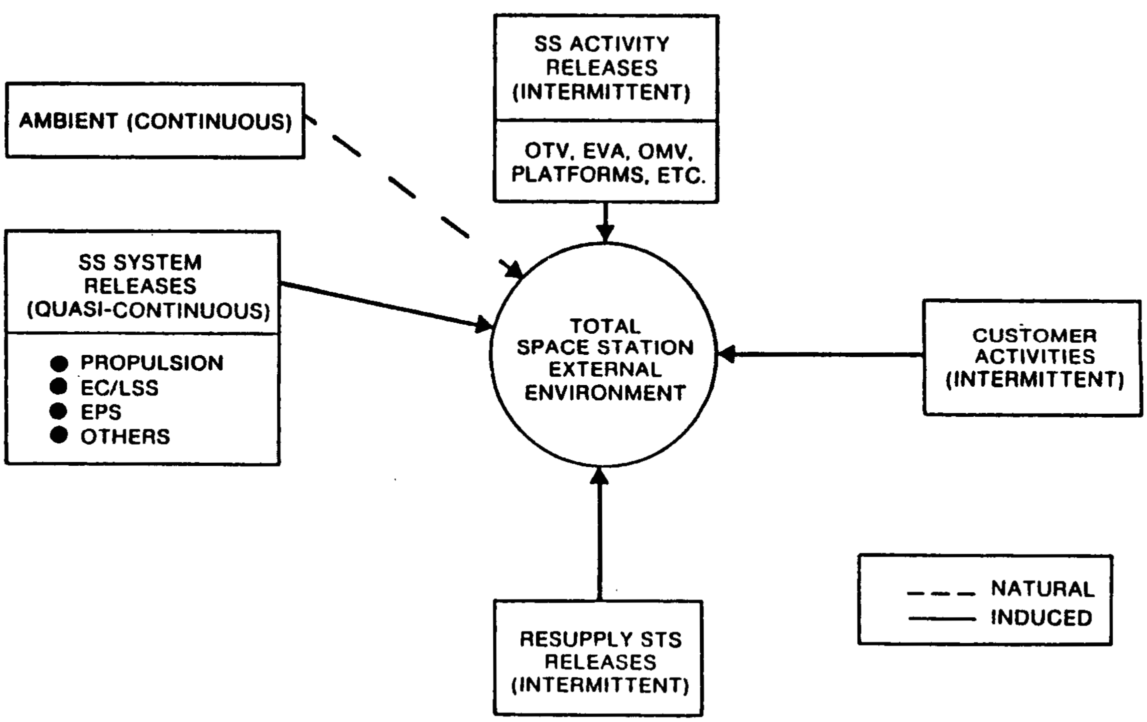

Figure 2-14. Total Space Station External Environment

drag makeup thrusting vis-a-vis observations from attached payloads and the optimum placement of thruster modules for least plume impact on station surfaces. For instance, the Solar Observatory Telescope (SOT) can only see the sun about 1 h in each 1.5-h orbit; other operations can be performed in the dark portion of the orbit where there is no interference with the SOT.

The contamination potential of a propulsion system depends on the following factors:

Propellants → Thruster Effluent Species →	• Molecular Species Column Densities • IR Absorption • Condensed Water
Propellant Flow Rate → Thruster Plume Density →	• Molecular Total Column Densities
Thrust Level and Thruster Nozzle Design → Backflow →	• Impingement

For the candidate propulsion systems, a number of evaluations were conducted. The dominant thruster effluent species and their relative amounts were determined for each system. The potential of the occurrence of thrust backflow was qualitatively assessed. Thruster backflow can cause plume impingement and deposition and/or condensation of the effluent on station surfaces. For this study, it was assumed that free-molecular flow nozzles for resistojets were feasible; therefore, no backflow would occur for a resistojet. Based on the thruster effluent species and the properties of the individual species, the potential of each specie for condensing on a surface was determined. Also, the absorption spectrum was obtained for each effluent species over the infrared wavelength range.

The comparative results of the contamination potential evaluation are presented in Table 2-9. In general, the candidate systems using only hydrogen have a lower contamination potential than the O_2/H_2 systems or the systems containing CO_2 or CH_4 resistojets. Although a hydrogen thruster can

Table 2-9. Contamination Comparisons

	Candidate System	Effluent		Backflow	Condensation	Infrared Absorption
		Gas	Amount*			
1	O_2/H_2 (MR = 4), Total	H_2O	High	Some	Possible	Selective
		H_2	Low	Some	No	No
2	Warm H_2, Total	H_2	High	Some	No	No
3	H_2 Resistojet (Reboost) + H_2/O_2 (ACS)	H_2O	Low	Some	Possible	Selective
		H_2	High	No	No	No
4	H_2 Resistojet (Reboost) + Warm H_2 (ACS)	H_2	High	Some	No	No
5	Electrolyzed O_2/H_2 (MR = 8), Total	H_2O	High	Some	Possible	Selective
6A	CO_2 Resistojet (154,000 Reboost) +	CO_2	High	No	Selective	Selective
	O_2/H_2 (MR = 4) (1,070,000 Resistojet)	H_2	Low	Some	No	No
		H_2O	High	Some	Possible	Selective
6B	CH_4 Resistojet (154,000 Reboost) +	CH_4	Low	No	Selective	Selective
	Warm H_2 (1,070,000 Resistojet)	H_2	Low	Some	No	No
		H_2O	High	Some	Possible	Selective
7A	CO_2 Resistojet (69,000 Reboost) +	CO_2	High	No	Selective	Selective
	Warm H_2 (1,155,000 Resistojet)	H_2	High	Some	No	No
7B	CH_4 Resistojet (69,000 Reboost) +	CH_4	Low	No	Selective	Selective
	Warm H_2 (1,155,000 Resistojet)	H_2	High	Some	No	No
8	O_2/H_2 (MR = 4) (854,000 Reboost)* +	H_2O	High	Some	Possible	Selective
	Warm H_2 (370,000 ACS)	H_2	Low	Some	No	No

*Amounts for 90-Day Impulses of 854,000 lb-sec (Reboost) + 370,000 lb-sec (ACS)

result in some thruster backflow, the hydrogen condensation temperature is so low (7.2°R) at vacuum conditions that condensation will not occur. Also, hydrogen does not appreciably absorb in the infrared spectra.

2.1.3.3 <u>Technical Risk</u>. Technical risk assessment conducted consisted of identifying the technology issues associated with each candidate system and a resolution of the critical nature of each identified issue. For the eight candidate systems, a total of five generic technology issues were defined. These included: (1) complex control system, (2) tank heating and gauging, (3) resistojet life, (4) water rocket life, and (5) electrolysis unit issues.

The control system issues involve the accumulator propellant mass gauging error, transport delay in control loop caused by long propellant lines, and the potential for compression heat contributing to accumulator overpressurization. The assessment of these technology issues was that these issues were not considered critical because technology exists to resolve the identified control system issues.

The propellant tank heating and gauging issue identified for supercritical pressure propellant storage was zero gravity propellant stratification influencing the propellant heating and mass gauging. This issue was not believed to be critical because a very small gravity level will avert stratification.

The technical issues associated with resistojets were the life of the thruster with different propellants, specifically the heating element, and the fact the resistojet free molecular flow had not been demonstrated. The longest demonstrated resistojet life has been in the 500 to 1,000-h range. These issues have subsequently been resolved through plume testing and through long life (10,000 h) tests.

Thrusters (water rockets) using oxygen and hydrogen from electrolyzed water (mixture ratio of 8) have a number of technical issues which can be resolved with current technology. The high mixture ratio of the water rocket results

in a lower delivered specific impulse and therefore will require a higher propellant weight (resupplied water if a dedicated water electrolysis is used) than conventional oxygen/hydrogen. The combustion at this stoichiometric mixture ratio results in a higher combustion temperature than at conventional oxygen/hydrogen mixture ratios, which requires the use of additional cooling. The technical issues identified with a water electrolysis unit were primarily related to system complexity and scaling current systems (350 psia) to high-pressure systems (1,000 psia to 3,000 psia). System complexity concerns included the need for a deionizer for the acceptance of all types of water, the need for dryers to remove entrained moisture in the product gas streams, and potential deterioration of cell electrochemical components. Long life of high-pressure electrolysis units has already been demonstrated in submarines and the development of units for ECLSS and electrical energy storage is proceeding under NASA aegis.

A summary of the identified technology issues is presented in Table 2-10. The single check (✓) in the control system and the tank heating and gauging columns indicates that only one propellant need be considered for the candidate systems using only hydrogen. As indicated in Table 2-10, the warm hydrogen system resulted in the least number of technology issues and the O_2/H_2 system with resistojets and the O_2/H_2 system integrated with ECLSS resulted in the most technology issues.

Table 2-10. Candidate System Technology Issues

System Number	Complex Control System	Tank Heating and Gauging	Resistojet Life	Water Rocket Life	Electrolysis Unit Issues
1	✓✓	✓✓			
2	✓	✓			
3	✓✓	✓✓	✓✓		
4	✓	✓	✓✓		
5				✓✓	✓✓
6	✓✓	✓✓	✓✓		
7	✓	✓	✓✓		
8	✓✓	✓✓			

2.1.3.4 Cost. Life-cycle costs (LCCs) for the eight propulsion system candidates were determined using Rocketdyne's LCC program (SSPSLCC). This LCC model was developed specifically for the SSPS to support the ongoing requirement and configuration trade studies. The model was conceived to be flexible in its structure in order to handle the large variations in propulsion concepts with regard to propellants, hardware, space station characteristics and operational support schemes.

The model categorizes LCC into four cost segments, i.e., development, production, transportation, and operational support. The methodology also includes cost risk. The results of the cost analysis are illustrated in Figure 2-15. Configurations using H_2 as a monopropellant have the lowest IOC cost, but the highest LCC. On the other side, the O_2/H_2 system with electrolysis has the highest initial cost but the lowest LCC, especially if all the water can be supplied by the STS and the space station waste water. The high IOC cost of this latter candidate system was caused by the inclusion of propulsion dedicated electrolysis unit development, production, and system integration

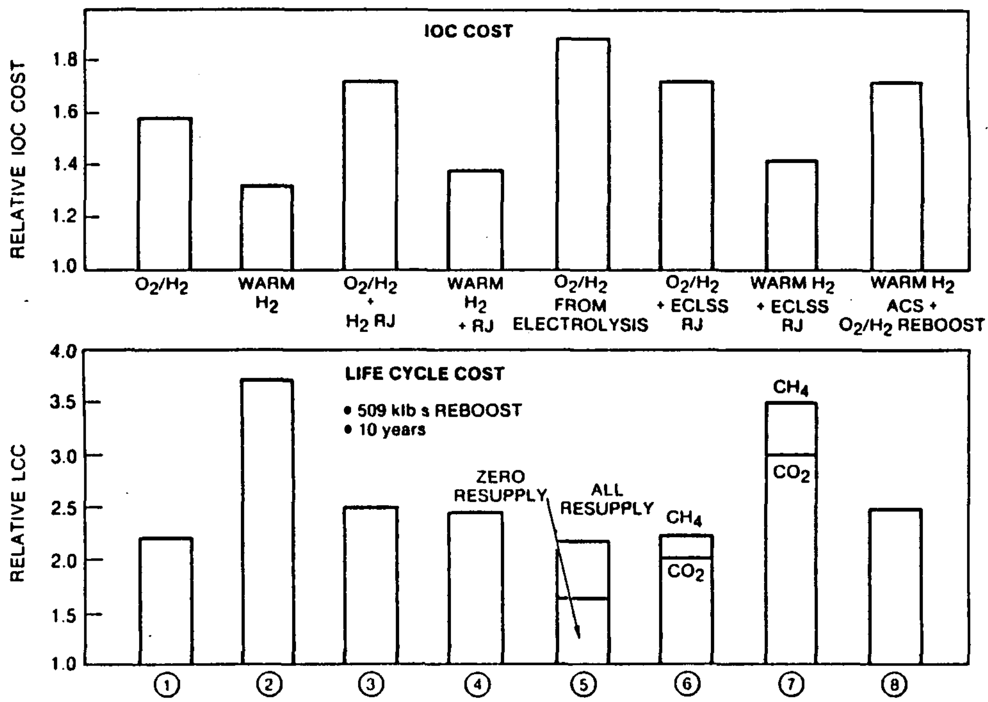

Figure 2-15. SSPS Cost Results

costs. If any or all of these costs are shared with other space station subsystems, or if further cost refinements reduce these costs, substantial reductions in IOC cost may be achieved. In any case, this candidate system will still have the lowest LCC.

A self-sufficient space station wherein all fluids are reprocessed and recirculated, and fluid resupply from Earth is minimized, is the ultimate stated goal and is in tune with the design-to-LCC (DTLCC) approach adopted for the space station program decision-making process.

Table 2-11 presents the IOC (or Phase C/D) and LCC drivers for each of the eight configurations. The control system (including health-monitoring), cryogenic tank development, and electrolysis are IOC cost drivers, while fluid resupply is in all cases (except the electrolysis configuration) the LCC driver. A typical LCC breakdown for the O_2/H_2 system of Configuration 1 is shown in Figure 2-16. Next to fluid resupply (i.e., transportation) cost, the research development, test, and engineering (RDT&E) cost is the largest contributor to LCC for this system.

From the cost analysis, it was concluded that (1) all warm H_2 system candidates have the lowest IOC costs, (2) the O_2/H_2 candidates have lower LCC if propellants are supplied from Earth, and (3) O_2/H_2 with electrolysis has the lowest LCC of all configurations and is the most attractive system with respect to LCC when water is STS or space station waste. Candidates with CO_2 resistojets were found to have lower LCC than those with the technically more difficult CH_4 resistojets.

2.1.3.5 <u>Growth Potential</u>. The growth of the space station can take on different dimensions. Potentially the dimensions can include: (1) higher total impulse requirement caused by a large electrical power system projected surface area; (2) higher propulsion system performance to reduce system resupply weight; (3) integration of the propulsion system with other space station systems; (4) reduced contamination; and (5) improved operational features.

Table 2-11. Cost Driver Comparison

SSPS Candidate System	IOC Cost Drivers	LCC Drivers
1 O_2/H_2	• Tank Development • Control System	• Fluid Supply
2 Warm H_2	• Control System • Tank Hardware	• Fluid Resupply • Initial Placement
3 O_2/H_2 + H_2 Resistojet	• Tank Development • Control System • Tank Hardware	• Fluid Resupply
4 Warm H_2 + H_2 Resistojet	• Control System • Tank Hardware	• Fluid Resupply
5 O_2/H_2 from Water Electrolysis	• Control System • Electrolysis Unit • Tank Development	• Initial Placement • Availability of Adequate Waste Water
6 O_2/H_2 with ECLSS	• Control System • Tank Development • Resistojet Development	• Fluid Resupply • Replacement Hardware Transport
7 Warm H_2 with ECLSS	• Control System • Tank Hardware	• Fluid Resupply • Initial Placement • Replacement Hardware Transport
8 Warm H_2 ACS + O_2/H_2 Reboost	• Control System • Tank Development	• Fluid Resupply

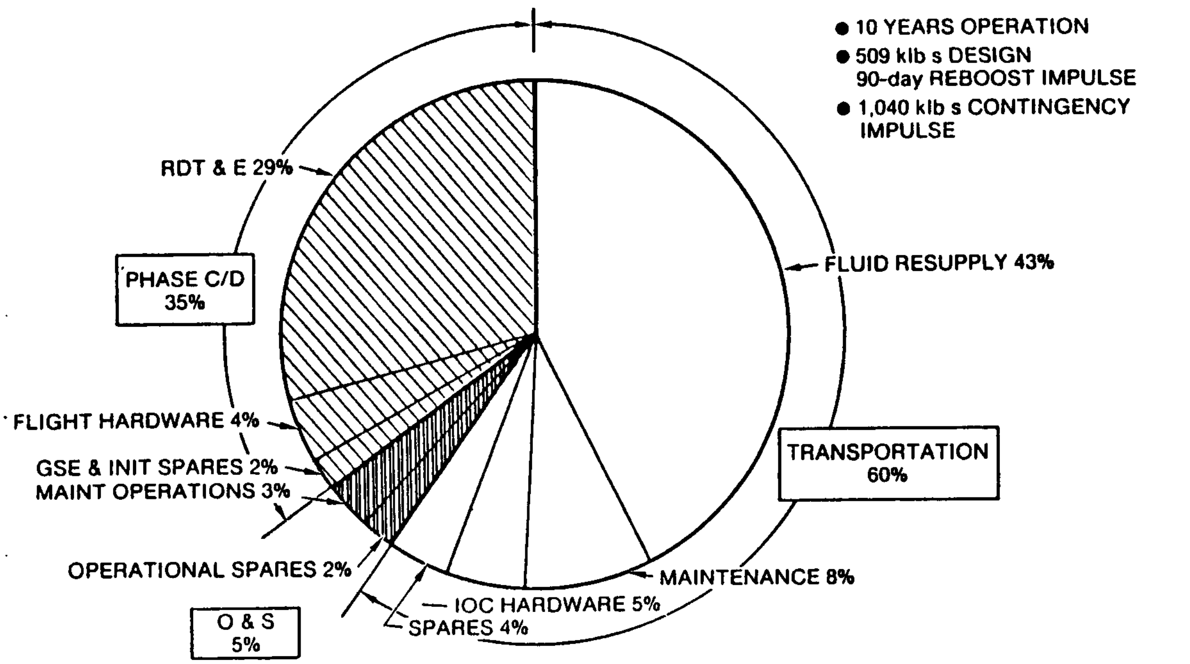

Figure 2-16. Life Cycle Cost Breakdown for the O_2/H_2 System of Configuration 1

Although the configuration of the growth station cannot be quantified at this time, the direction will be to minimize resupplied propellant and utilize waste products. This direction will lead to the full utilization of ECLSS waste products, orbital transfer vehicle (OTV) propellant depot boil-off, manufacturing process wastes, and water electrolysis. The potential on-board propellant sources, the produced propellant, and the potential growth propulsion systems are presented in Table 2-12. A representative O_2/H_2 system growth path is illustrated in Figure 2-17. The initial system in this example is a supercritical O_2/H_2 system, which transforms into a water electrolysis O_2/H_2 system, and then to a fully integrated O_2/H_2 system with multipropellant resistojet being supplied propellant from the on-board sources.

The growth potential criteria considered included ease of modular upgrading, ease of integration with other station systems, and the relative cost of scarring. As shown in Table 2-13, the candidate systems with minimal integration with other space station systems (O_2/H_2, warm H_2, O_2/H_2 with H_2 resistojets, warm H_2 with H_2 resistojets, and warm H_2 ACS with O_2/H_2 drag makeup) are the easiest to upgrade modularly. Conversely, the candidate system with more space station system integration (O_2/H_2 system with dedicated water electrolysis, O_2/H_2 system integrated with ECLSS, and the warm H_2 system integrated with ECLSS) would result in easier space station integration and lower station scarring cost.

2.1.3.6 <u>Operational Utility</u>. The operational utility assessment considered launch packaging and station keel storage volume, station buildup, propellant availability, ease of initial deployment, refueling complexity, and system maintainability. All the candidate propulsion systems incorporate accumulators near the thrusters and therefore can provide propulsion modules for early space station buildup. Also, all the candidate systems can provide thrust on short notice (propellant availability).

In considering launch packaging and station keel storage volume, the O_2/H_2 candidate systems (see Figures 2-10 and 2-12) resulted in the lowest volume requirements. For the initial deployment, the single propellant, warm H_2

Table 2-12. SSPS Growth Direction

Potential Space Station On-Board Propellant Sources	Propellants	Potential Growth SSPS
Water Electrolysis	O_2 and H_2	O_2/H_2 with H_2
OTV Propellant Depot and EPS SAVE Haven Boiloff	H_2 and Possibly O_2	
ECLSS	CO_2 or CH_4, Water, and/or Other Gases	CO_2, CH_4, or Other Gas Resistojets
Manufacturing Processes		

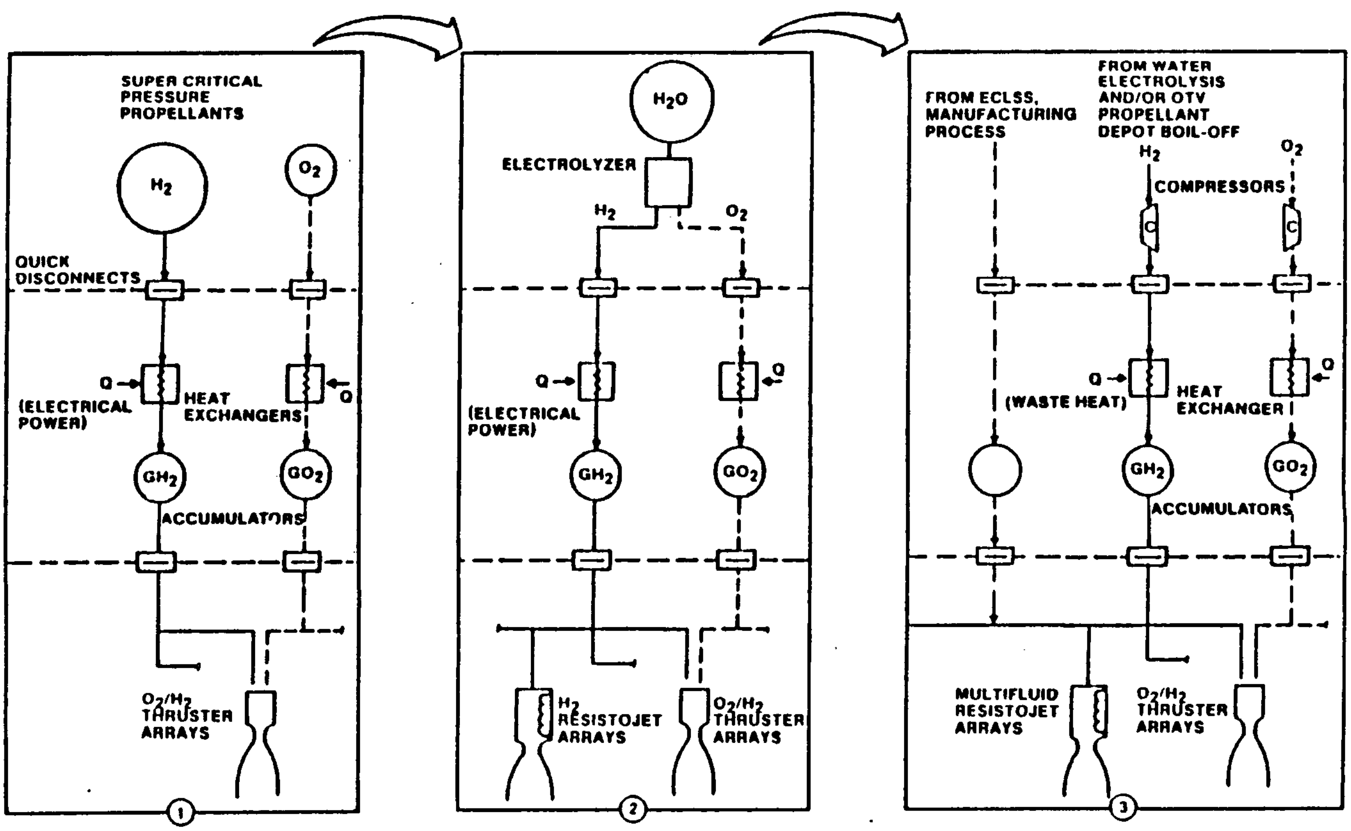

Figure 2-17. Representative O_2/H_2 SSPS Growth Path

Table 2-13. SSPS Growth Potential Assessment

Growth Potential Criteria	Evaluation Result	Comments
• Ease of Modular Upgrading • Increased Total Impulse	• Easy: O_2/H_2, warm H_2, O_2/H_2 with H_2 resistojets, warm H_2 with resistojets, and combined alternate	• Simply add more or larger propellant tanks
	• Some Difficulty: O_2/H_2 and warm H_2 integrated with ECLSS	• Requires significantly more electrical power
	• More Difficult: O_2/H_2 from water electrolysis	• Substantially more electrical power consumption
• Relative Cost of Scarring	• Lower: O_2/H_2 with H_2 resistojets, warm H_2 with H_2 resistojets, O_2/H_2 from water electrolysis, O_2/H_2 and warm H_2 integrated with ECLSS	• Minimal system modifications
	• Higher: O_2/H_2, warm H_2, and combined alternate	• Requires significant system modifications (multifluid) resistojet, ECLSS integration
• Ease of Integration • Other Space Station System	• Easy: O_2/H_2 from water electrolysis, O_2/H_2 and warm H_2 integrated with ECLSS	• Minimal system modifications
• Other SSPEs	• Some Difficulty: Rest of candidate systems	• Requires additional system modifications

system would be the simplest to deploy. The candidate systems which are integrated with the ECLSS or water electrolysis have the most connections and therefore would be the most complex to deploy. The ECLSS integrated candidate systems utilize waste products as propellants and therefore minimize propellant resupplied from Earth and simplify propellant resupply. The O_2/H_2 system with dedicated water electrolysis uses either inert (safe), high density water resupplied from Earth and simplifies propellant resupply or uses STS/station waste water, eliminating resupply.

From a system maintainability standpoint, all candidate systems would be designed for modularity to facilitate maintenance and minimize extra-vehicular activity (EVA). Components requiring maximum replacement times include the oxygen tanks, oxygen heat exchangers, and the quick disconnects. The maintenance of oxygen components should be minimized for safety reasons.

In summary, the O_2/H_2 system with dedicated water electrolysis would be the easiest system to maintain (repair and replace). All other O_2/H_2 candidate systems tend to be more complex to maintain.

2.1.3.7 Potential Space Station Program Element (SSPE) Integration. The assessment of the potential SSPE integration considered the autonomy of the propulsion system candidate with regard to energy needs and resupplied propellant and the potential beneficial interaction with other SSPE systems (ECLSS, electrical power system (EPS), manufacturing processes, OTV, and platforms). The assessment results are presented in Table 2-14. From a propulsion system autonomy standpoint, candidates with less hydrogen were more favorable. Hydrogen requires more energy to thermally condition and requires larger and heavier propellant tanks. Considering autonomy, the most favorable candidate systems were the O_2/H_2 system and the O_2/H_2 system integrated with the ECLSS.

The benefit of integrating the propulsion system with other station systems can be significant. For example, integration with the ECLSS and/or manufacturing process can result in utilization of ECLSS or manufacturing waste

Table 2-14. Potential SSPE Integration Assessment

SSPE Integration Criteria	Evaluation Result	Comments
• Propulsion System Autonomy • Minimum Energy Requirements	• Low: O_2/H_2 and combined alternate	• O_2/H_2 energy consumption - low (tank pressurization & thermal conditioning)
	• High: O_2/H_2 from water electrolysis	• Water electrolysis consumes large total energy but at low rate
• Minimum Resupplied Propellants	• Low: O_2/H_2 from water electrolysis if water is free, O_2/H_2, O_2/H_2 integrated with ECLSS	• High performance; smaller and lighter tanks
	• High: Warm H_2	• Low performance; larger and heavier heavier tanks
• Beneficial Interaction with other SSPE Systems		
• ECLSS	• Candidate systems integrated with ECLSS and O_2/H_2 from water electrolysis	• Systems can use ECLSS waste products and/or excess water
• EPS Safe Haven • Commonality	• All candidate systems except O_2/H_2 from water electrolysis	• Systems can use common storage approach
• Use of Boiloff/Vent	• All candidate systems	• Require compressors
• Manufacturing Processes	• Candidate system integrated with ECLSS, O_2/H_2 from water electrolysis and systems with H_2 resistojets	• Wastes used in multifluid resistojets
• OTV Boiloff	• All candidate systems	• Require compressors
• Platform commonality	• Possibly O_2/H_2, warm H_2	• Can not use systems integrated with ECLSS • Large power required for resistojets and water electrolysis

products and excess water for propulsion propellant. This can significantly reduce resupply costs. The O_2/H_2 and warm H_2 systems integrated with the ECLSS definitely derive benefits from interaction with ECLSS, EPS, manufacturing and the OTV. The O_2/H_2 and the warm H_2 systems could provide commonality with the platforms.

2.2 CONCEPT RATING CONCLUSION AND RECOMMENDATION

The rating/ranking results of the SSPS candidates are summarized in Figure 2-18 and Tables 2-15 and 2-16. As shown in Figure 20, the warm H_2 system achieved the highest overall rating, with the warm H_2 system with H_2 resistojets second, the O_2/H_2 system third, the O_2/H_2 water electrolysis system fourth, and the combined warm H_2 ACS and O_2/H_2 reboost system fifth. The order of the rankings remained unchanged with weighted or unweighted factors (Figure 2-18). Table 2-15 presents the weighted numerical ratings of each system with respect to all selection criteria. The detailed

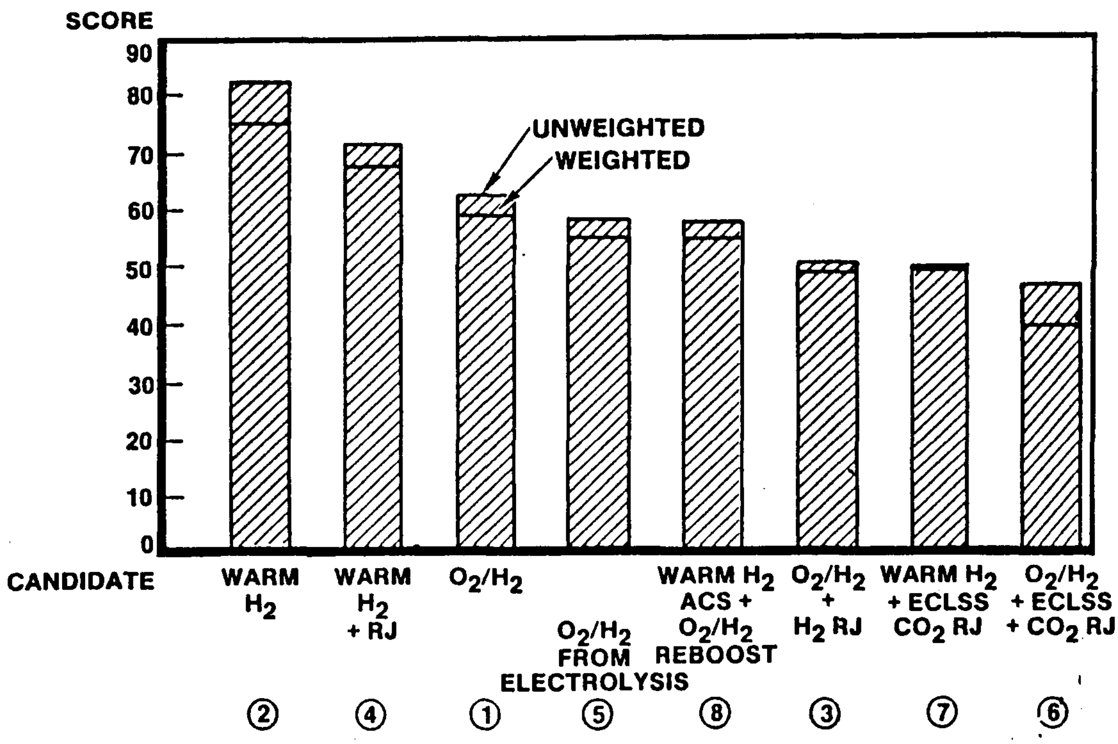

Figure 2-18. Propulsion System Candidate Rating Results

Table 2-15. Evaluation Score Summary

		System Candidate							
Criteria	Wt	1 O_2/H_2	2 Warm H_2	3 O_2/H_2 H_2 RJ	4 Warm H_2 H_2 RJ	5 O_2/H_2 Electrolysis	6 O_2/H_2 CO_2 RJ	7 Warm H_2 CO_2 RJ	8 O_2/H_2 Drag H_2 ACS
Reliability and Safety	30	12.3	29.6	9.8	20.1	13.1	5.3	16.1	13.7
Contamination Potential	16	6.7	16.0	6.7	16.0	6.7	4.0	4.0	6.7
Technical Risk	15	15.0	15.0	10.0	10.0	6.3	5.0	5.0	15.0
IOC and Life Cycle Cost	13	9.2	6.5	6.5	10.5	11.5	8.6	8.1	6.7
Growth Potential	11	6.4	6.4	9.2	9.2	9.2	9.2	9.2	6.4
Operational Utility	10	4.8	4.4	4.8	3.1	7.6	4.8	3.8	3.1
SSPE Integration	5	3.6	3.6	1.5	2.1	1.5	2.5	2.5	3.5
Total	100	58.0	81.5	48.5	71.0	55.9	39.4	48.7	55.1

Table 2-16. Candidate Systems Evaluation Criteria

Criteria	Wt	1 R	1 WR	2 R	2 WR	3 R	3 WR	4 R	4 WR	5 R	5 WR	6 R	6 WR	7 R	7 WR	8 R	8 WR
● Reliability and Safety	30	0.41	12.3	0.99	29.6	0.33	9.8	0.67	20.1	0.44	13.1	0.18	5.3	0.54	16.1	0.46	13.7
● Simplicity of Concept		0.5		1.0		0.25		0.25		0.25		0.25		0.25		0.5	
● Number of Components		0.42		0.95		0.35		0.7		0.65		0.14		0.65		0.52	
● Number/Severity of Potential Safety Hazards		0.25		1.0		0.25		1.0		0.25		0.25		1.0		0.25	
● Operating Procedure Complexity		0.5		1.0		0.5		0.5		0.5		0.25		0.25		0.5	
● Number of Life/MTBF Limiting		0.38		0.98		0.28		0.9		0.54		0.0		0.54		0.52	
● Contamination Potential	16	0.42	6.7	1.0	16.0	0.42	6.7	1.0	16.0	0.42	6.7	0.25	4.0	0.25	4.0	0.42	6.7
● Exhaust Plume Impingement		0.5		1.0		0.5		1.0		0.5		0.25		0.25		0.5	
● Effluent Contamination Potential		0.25		1.0		0.25		1.0		0.25		0.25		0.25		0.25	
● Plume Radiation and Optical Effects		0.5		1.0		0.5		1.0		0.5		0.25		0.25		0.5	
● Technical Risk	15	1.0	15.0	1.0	15.0	0.67	10.0	0.67	10.0	0.42	6.3	0.33	5.0	0.33	5.0	1.0	15.0
● Technology Readiness		1.0		1.0		0.5		0.5		0.5		0.25		0.25		1.0	
● Technology Uncertainty		1.0		1.0		0.5		0.5		0.5		0.25		0.25		1.0	
● Sensitivity to Space Station Configuration		1.0		1.0		1.0		1.0		0.25		0.5		0.5		1.0	
● IOC and Life Cycle Cost	13	0.71	9.2	0.5	6.5	0.5	6.5	0.81	10.5	0.89	11.5	0.66	8.6	0.62	8.1	0.52	6.7
● IOC (Phase C/D) Cost		0.55		1.0		0.3		0.87		0.55		0.32		0.82		0.31	
● Life Cycle Cost		0.87		0.0		0.7		0.74		1.22		1.0		0.42		0.72	
● Growth Potential	11	0.58	6.4	0.58	6.4	0.83	9.2	0.83	9.2	0.83	9.2	0.83	9.2	0.83	9.2	0.58	6.4
● Ease of Modular Upgrading		1.0		1.0		1.0		1.0		0.5		0.5		0.5		1.0	
● Cost of Scarring for Growth		0.25		0.25		1.0		1.0		1.0		1.0		1.0		0.25	
● Integration with Growth Space Station		0.5		0.5		0.5		0.5		1.0		1.0		1.0		0.5	
● Operational Utility	10	0.48	4.8	0.44	4.4	0.48	4.8	0.31	3.1	0.76	7.6	0.48	4.8	0.38	3.8	0.31	3.1
● Launch Packaging/Keel Storage		0.9		0.0		0.9		0.0		0.55		0.93		0.27		0.48	
● Ease of Deployment		0.5		1.0		0.5		0.5		0.5		0.25		0.25		0.25	
● Refueling Mode		0.25		0.25		0.25		0.25		1.0		0.5		0.5		0.25	
● Ease of Repair/Restoration		0.25		0.5		0.25		0.5		1.0		0.25		0.5		0.25	
● Potential SSPE Integration	5	0.73	3.6	0.73	3.6	0.3	1.5	0.43	2.1	0.3	1.5	0.5	2.5	0.5	2.5	0.7	3.5
● Propulsion System Energy Requirement		0.95		0.7		0.35		0.35		0.1		0.5		0.5		0.9	
● Interaction With Other SS Subsystems		0.5		0.75		0.25		0.5		0.5		0.5		0.5		0.5	

Note: R = Rating and WR = Weighted Rating

breakdown to the subcriteria level is presented in Table 2-16. Therefore, these top five candidate systems were recommended to NASA-MSFC for preliminary design evaluation.

As shown in Tables 2-15 and 2-16, the two H_2 systems had the highest reliability and safety rating (highest weighted criteria) because these systems were simple (one propellant) with the lowest number of components. Since only H_2 is discharged, these same two candidate systems had the lowest contamination potential and therefore the highest contamination potential rating. The lowest technical risk (highest technical risk rating) was achieved by the O_2/H_2 system, the warm H_2 system, and the combined H_2 ACS with O_2/H_2 reboost. The technology for these candidate systems is well in hand.

The O_2/H_2 water electrolysis system resulted in the highest IOC and LCC rating because of the greatly reduced operational costs. However, the warm H_2 system with H_2 resistojets also achieved a high IOC and LCC rating because of a combination of a low development cost and a low resupply cost (high delivered specific impulse of resistojets). Candidate systems with resistojets and O_2/H_2 water electrolysis are attractive from a growth potential standpoint because of lower resupply cost. Also, candidate systems integrated with the ECLSS reduce growth station scarring and permit integration with other space station systems, and therefore, these systems had the highest growth potential ratings. From an operational utility standpoint, the O_2/H_2 water electrolysis candidate achieved the highest rating because of its repairability and simple water resupply. Because of their low energy requirements and their compatibility with platform propulsion requirements, the O_2/H_2 and the warm H_2 systems achieved the highest SSPE integration rating.

This analytical task resulted in many technical conclusions regarding the SSPS. These include the fact that accumulators enable the decoupling of the propellant tank pressurization and propellant thermal conditioning from the thruster operation. The lowest system and resupply weight and volume were achieved by the O_2/H_2 system. The addition of H_2 resistojets was

extremely beneficial to the warm H_2 system in terms of significant reductions in system weight and volume. In addition, the utilization of resistojets can provide the capability of high velocity propulsive disposal (free molecular flow) of ECLSS and on-board manufacturing processes waste products. Although an in-depth study of contingency propellant storage was not performed, ambient propellant storage would be preferred over cryogenic storage because of its simplicity. Ambient propellant storage would definitely be the preferred choice if the contingency total impulse was low; however, if the contingency total impulse requirements are high, cryogenic propellant storage may be required to reduce storage volume.

Based on customer needs, OTV propellant depot (O_2 and H_2), ECLSS evolution, and shuttle orbiter excess propellants, a fully integrated hydrogen, oxygen, and water economy can be envisioned for the space station. If this is accomplished, significant cost and operational benefits are possible. The SSPS, ECLSS, shuttle orbiter, and the station manufacturing facilities would be combined into a single system that would utilize common O_2/H_2 storage and waste water electrolysis facilities. Waste fluids from ECLSS and manufacturing facilities would be recycled to produce potable water, oxygen, and hydrogen for use by the station customers. The SSPS would have the flexibility to use water products that might not economically be recycled for use by station customers and balance the on-orbit supply of oxygen and hydrogen.

Overall, the results of this study clearly indicated that oxygen/hydrogen-based propulsion systems can provide simple, low cost, and viable systems for the IOC space station. Furthermore, these systems can eventually provide the basis for an oxygen, hydrogen, and water economy for a fully integrated space station.

Subsequent to the completion of this study, the Space Station Change Control Board baselined the water electrolysis O_2/H_2 concept with multifluid resistojets. This decision was based on this study, and independent studies by Boeing, Martin-Marietta, Jet Propulsion Laboratory, LeRC, and MSFC. Additionally, thruster test results at MSFC for the 8:1 mixture ratio life of

1-million lb-s were a central element. The critical deciding factor was the elimination of propellant logistics (both up full and down empty) and of waste disposal (de-orbit or carry down). Based on this rebaselining, the overall test bed effort was redirected to address issues relating to the water electrolysis approach as listed in Table 2-10 and accompanying text.

3.0 TEST BED DESIGN AND FABRICATION

The system design goal was to provide a test bed representative of a SSPS capable of demonstrating the readiness of oxygen/hydrogen propulsion technology for the IOC space station application. In addition, the system must be flexible enough to evaluate various supply concepts and components for use on the IOC and the growth stations.

To accomplish these goals, the test bed was designed with two basic modules: a propulsion module containing propellant storage and thruster modules, and a propellant supply module. The propulsion module contained oxygen and hydrogen accumulator tanks, a resistojet propulsion module, and a 25-lbf thrust engine module and associated control valves all mounted in a 9-ft cube structure to simulate the basic building block structural element of the space station (Figures 3-1 and 3-2). The design accommodates various types of fluid supply modules connected to the propulsion module in order to simulate a complete system (Figure 3-3) and to study growth configuration or other applicable approaches. A supercritical gas storage tank system was designed for the test bed, however, because of the subsequent baseline of the electrolysis system, it was never fabricated.

With the addition of water electrolysis to the baseline space station system for the propellant supply, the need for an electrolysis system operation on the test bed became apparent. As a result, the program was realigned and an electrolysis module was designed and fabricated at Rocketdyne to fit on top of the existing test bed propulsion module cube. Components to be tested on the module included Arde steel tanks, SCI graphite wrapped tanks, a LSI electrolysis unit, and a HSD electrolysis unit.

The module included canisters to contain each of the water electrolysis units not designed to be operable in a vacuum. Molecular-sieve dryers designed by Boeing and fabricated at MSFC, were also included on the module. Figure 3-4 shows the module assembly in the workshop before installation. In Figure 3-5, an LSI technician is connecting the LSI 350-psig water electrolysis unit to

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Figure 3-1. Test Bed Assembly

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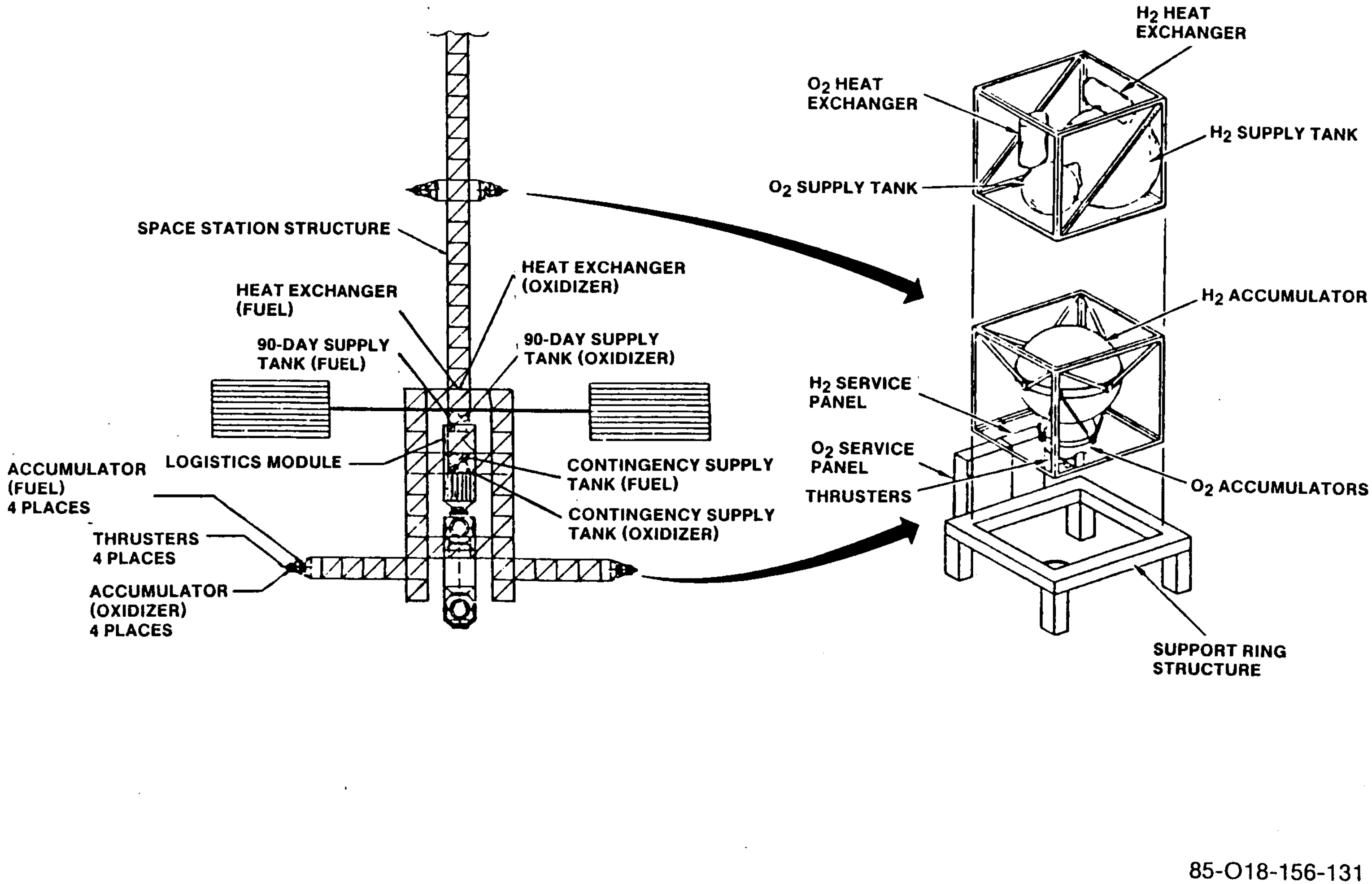

Figure 3-2. Preliminary Flight System-to-Test Bed Design

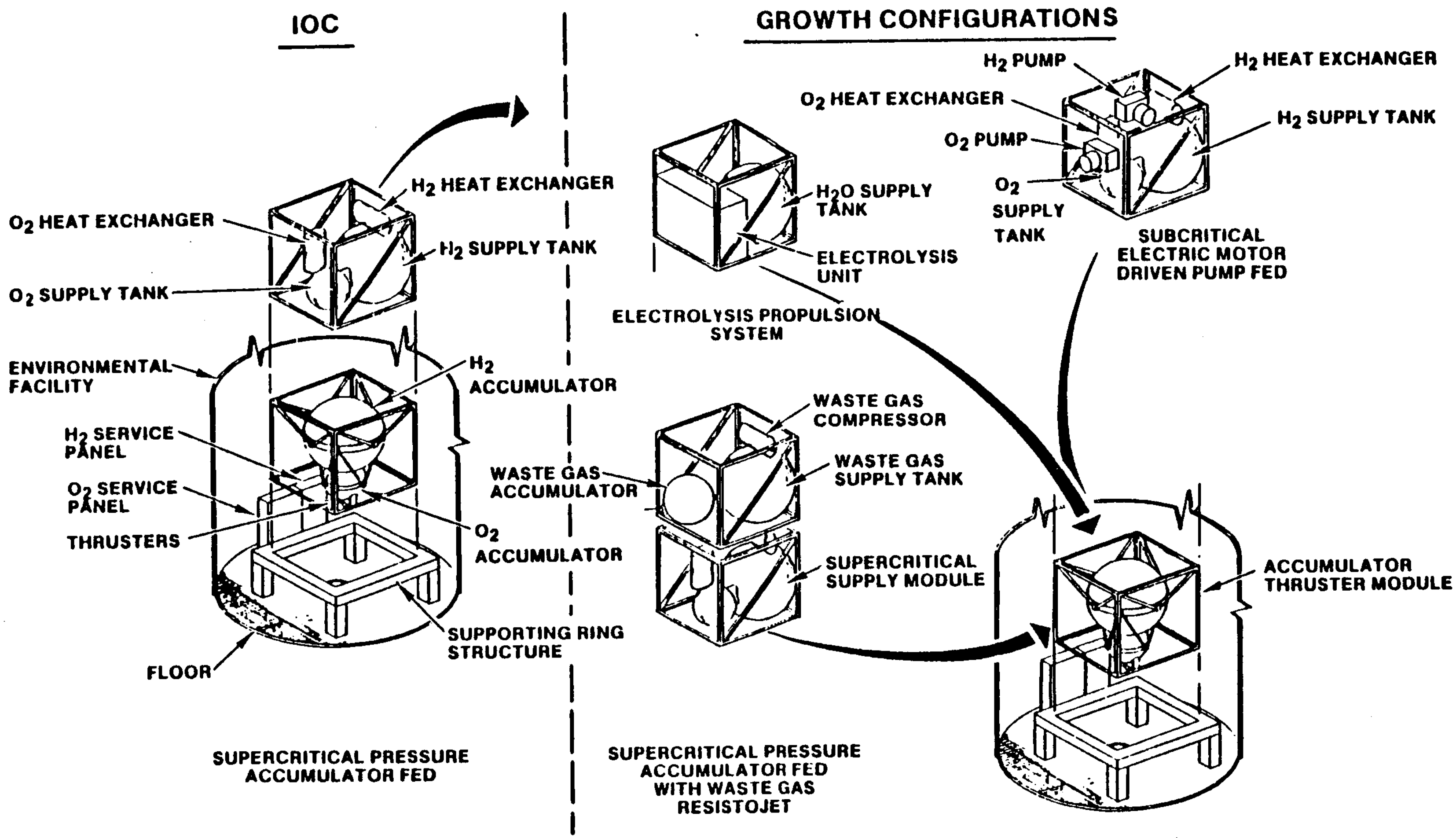

Figure 3-3. SSPS Test Bed Growth Evolution

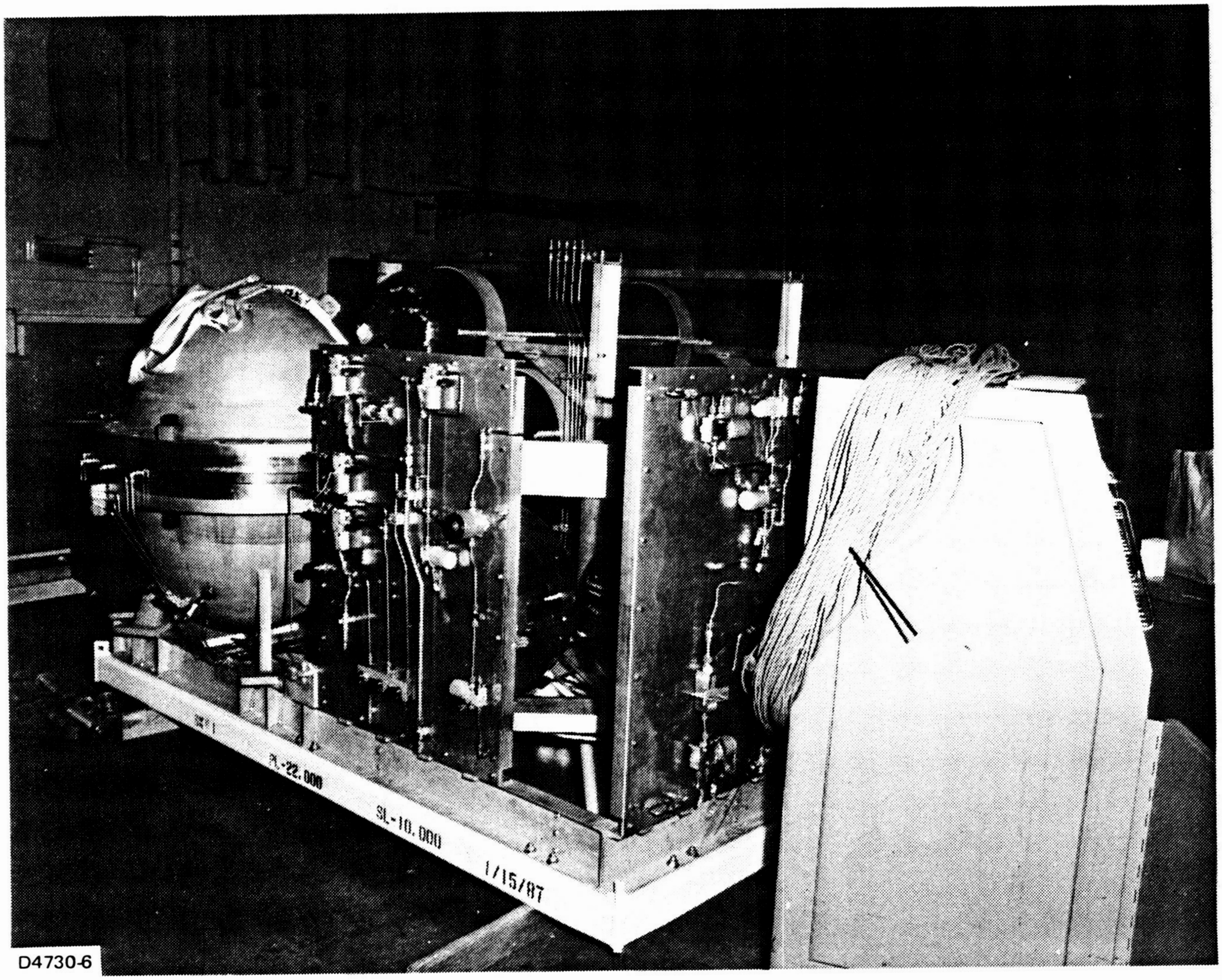

Figure 3-4. Water Electrolyte Module in MSFC Workshop

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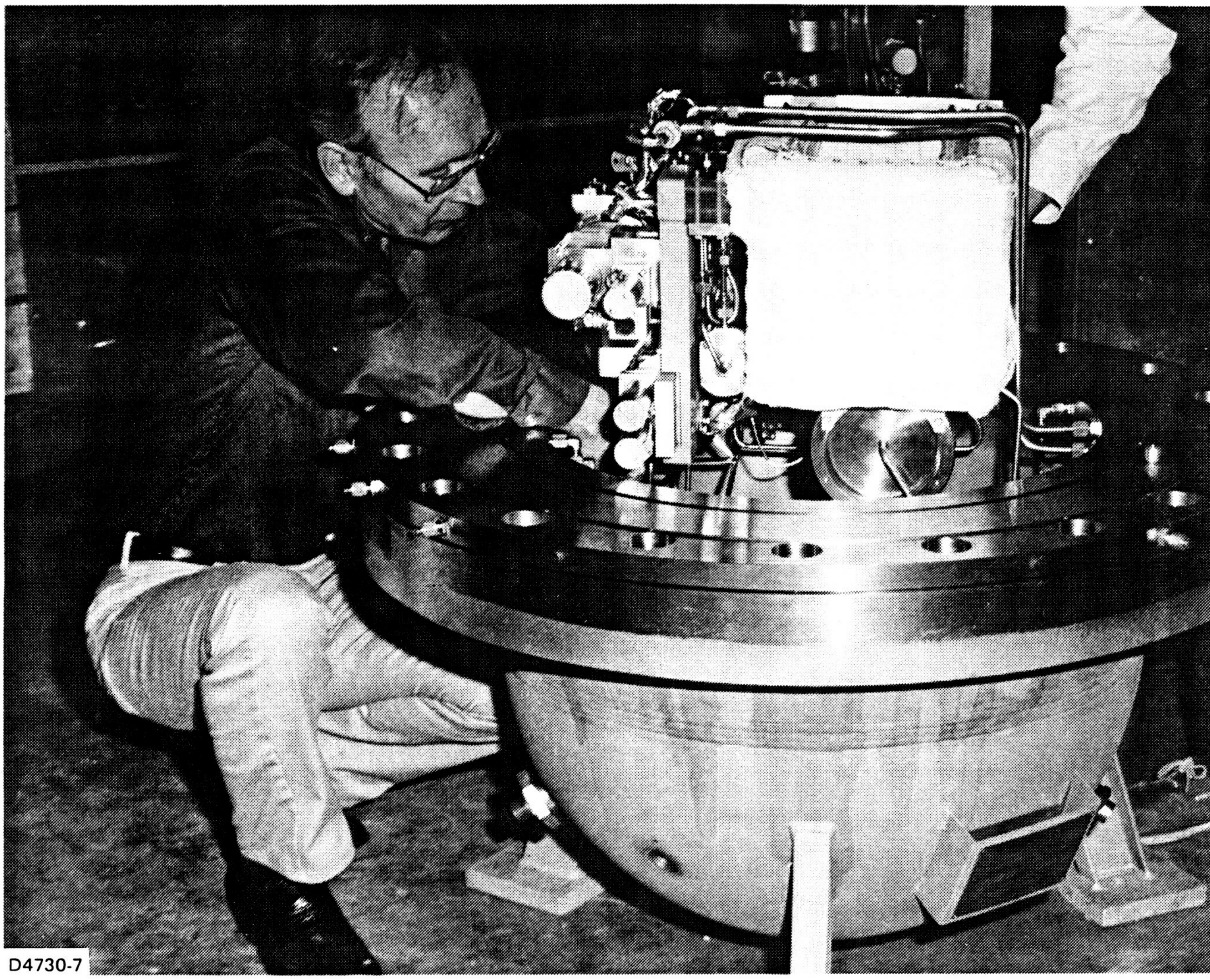

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Figure 3-5. LSI Technician Connecting Electrolysis Unit to Pressure Container Pass Throughs

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the container ports. Figures 3-6 and 3-7 show the installation of the module into the test facility. Figure 3-8 displays a simplified schematic of the electrolysis based propulsion system test bed.

The man-walk platform and safety rails added to the electrolysis pallet at MSFC can be seen in Figures 3-6 and 3-7. The basic drawings that were used to fabricate the test bed propulsion module and electrolysis module are included in Appendix A. A complete detailed understanding of the test bed can be obtained by detail study of the documents presented there. Included within the body of the report are the essential details and design parameters of the propulsion module, the cryogenic supercritical storage module, and the electrolysis module.

3.1 PROPULSION MODULE DESIGN SUMMARY

The test bed was designed for testing in MSFC vacuum Test Cell 302 at an ambient pressure of 1 torr (Figure 3-9). Valve and control components were selected from standard commercial equipment to provide simulation of flight hardware without the expense and time required to obtain flight components and with the belief that little was lost to the technology demonstrations. Updating to flight-type equipment was possible on a component by component basis as truly representative hardware could be defined and made available. All line assemblies were fabricated of welded tubing with Cajon-VCR fittings used on all removable joints and components to accommodate the low vacuum pressures. A schematic of the propulsion module is shown in Figure 3-10. Tables 3-1 and 3-2 summarize the components used and their design operating ranges.

The propulsion module oxygen and hydrogen valves and control components were separated and mounted on two panels beneath the tanks on opposite sides of the structural cube. A third panel mounted in the center of the cube contained the resistojets and engine module components. The components and plumbing were mounted to provide easy access (Figure 3-11) for repair or replacement with flight-type components as available.

Figure 3-6. Installation of Water Electrolysis Module into Stand

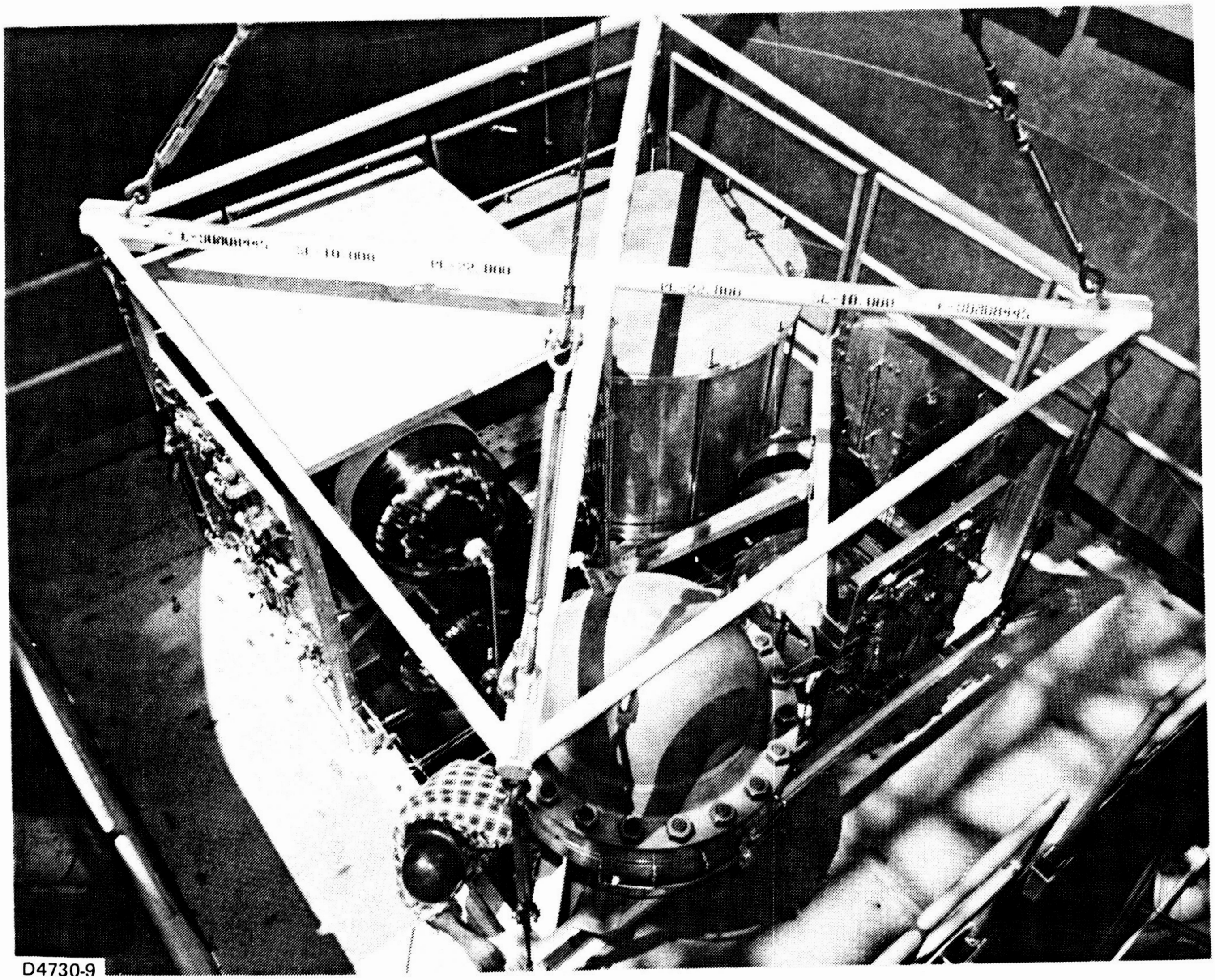

Figure 3-7. Water Electrolysis Module Installed
on Top of Accumulator Module in Stand

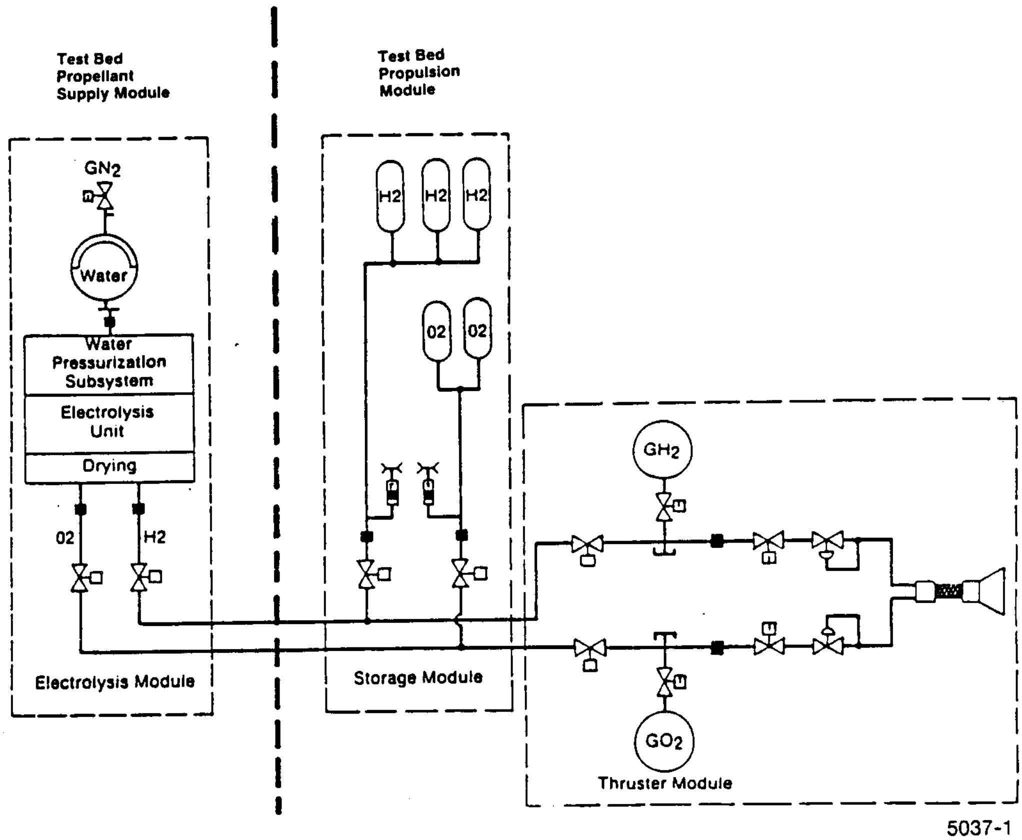

Figure 3-8. Simplified Schematic of Space Station Propulsion Test Bed

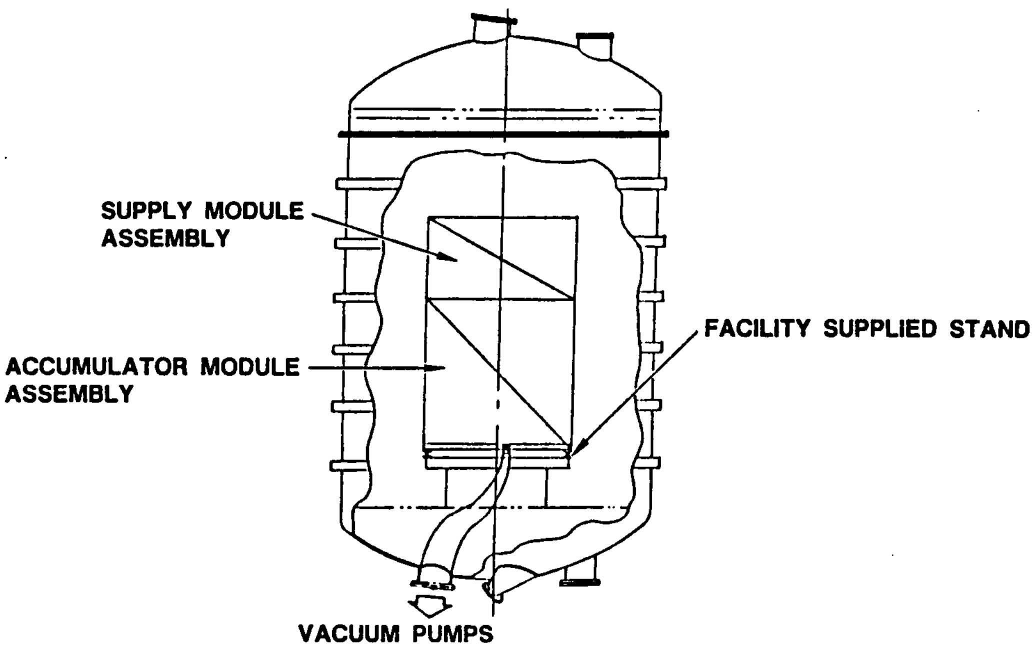

Figure 3-9. Space Station O/H_2 Propulsion Test Bed (Test Position 302 Vacuum Chamber Vertical Installation)

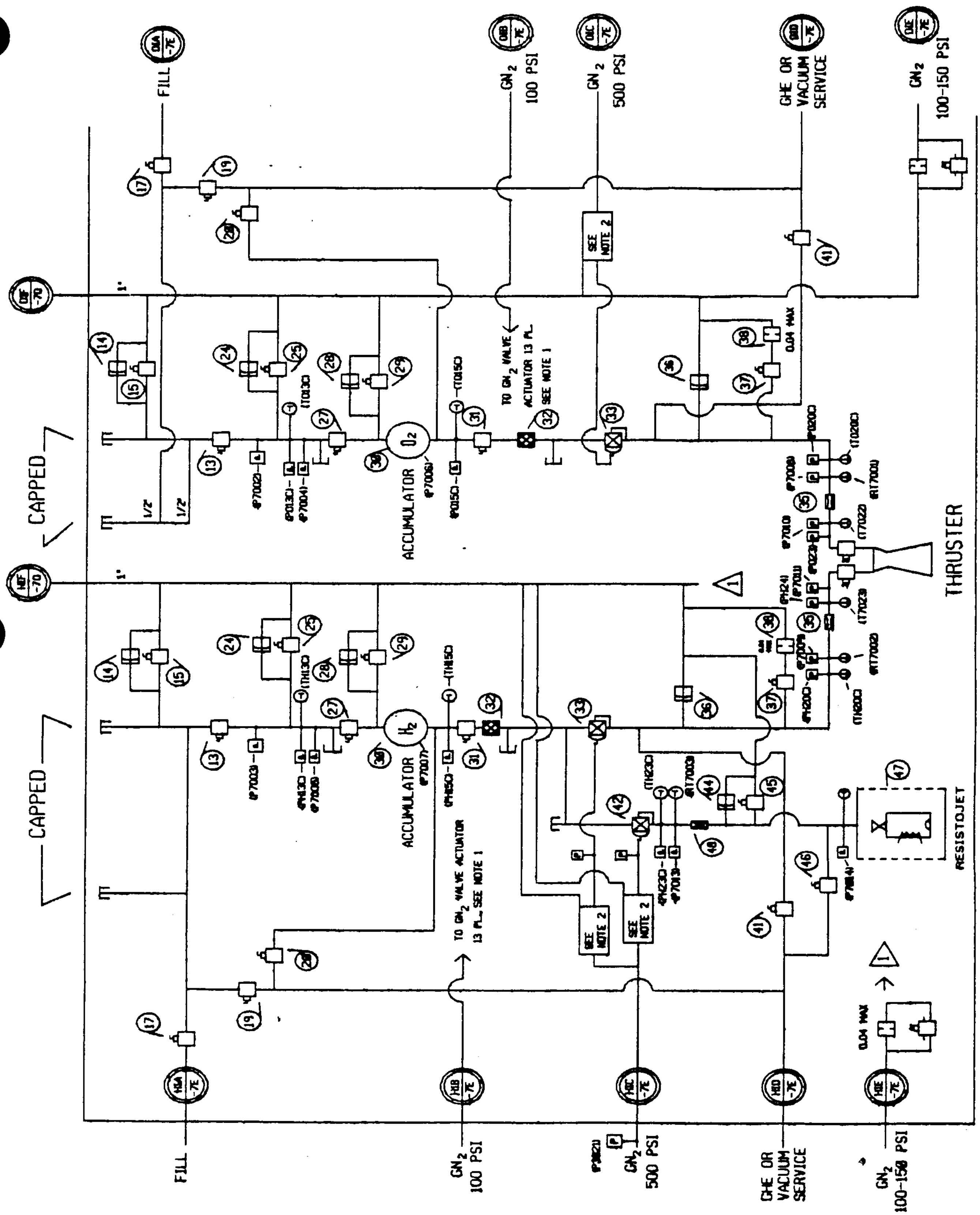

Figure 3-10. Propulsion Module Schematic

Table 3-1. Component Operating Ranges

	TEST BED SUBSYSTEM OPERATING RANGES								
	OPERATING PRESS psig			VENT PRESS psig		TEMPERATURE deg R			FLOW lb/s
	NOM	MAX	MIN	MAX	MIN	NOM	MAX	MIN	NOM
STORAGE TANK O2	1000	1350	200	1500	1365	160	600	160	0.188
H2	750	1000	200	1100	1000	40	600	40	0.047
HEAT EXCHANGER O2	1000	2200	200	2500	2275	—	600	160	0.188
H2	750	2200	200	2500	2275	—	600	40	0.047
ACCUMULATOR O2	1000	1600	200	1800	1635	400	600	300	0.188
H2	750	1300	200	1500	1365	300	600	200	0.047
THRUSTER MODULE O2	145	250	100	300	260	530	600	395	0.047
H2	190	250	100	300	260	530	600	395	0.012
GN2 VALVE ACTUATORS	125	220	100	—	—	530	600	500	
VACUUM SERVICE	—	—	1 TORR	—	—	530	—	—	
GN2 REGULATORS	500	500	0	—	—	530	—	—	

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Table 3-2. Component Survey

VALVES
- NUPRO "U" SERIES BELLOWS VALUE
- PNEUMATIC OPERATOR - ELEC. HEATER
- BODY - 316 SS
- BELLOWS - 347 SS
- SEAT INSERT — KEL-F (BATCH TESTED FOR O_2)
  ALTERNATE - STELLITE

FILTERS
- VACCO INDUSTRIES
- IN LINE FILTER
- DISC TYPE
- VIKING FILTER - MODIFIED FITTINGS
- ALL METAL - 304-L (O_2), 316-L (H_2)

LINES
- 321 SS SEAMLESS TUBING

FITTINGS
- CAJON-VCR
- 316 AND 316-L SS
- GASKETS - SILVER PLATED 316

ACCUMULATOR TANKS
- ASME CODED VESSEL
- O_2 - 304L
- H_2 - 316L
- GRAYLOC CLOSE OUT FLANGES

REGULATORS
- GROVE MODEL 94
- BATCH TESTED SOFT GOODS FOR O_2

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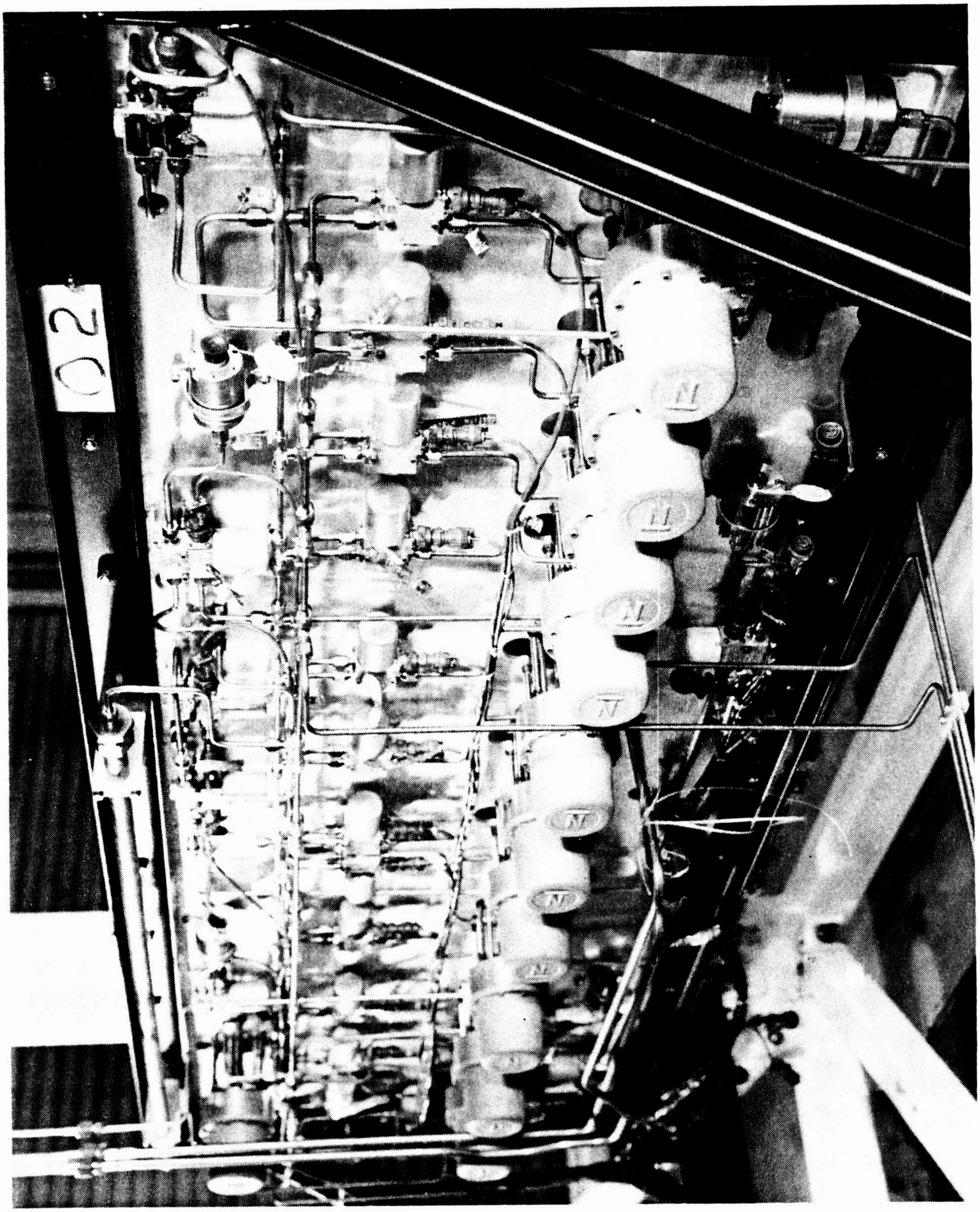
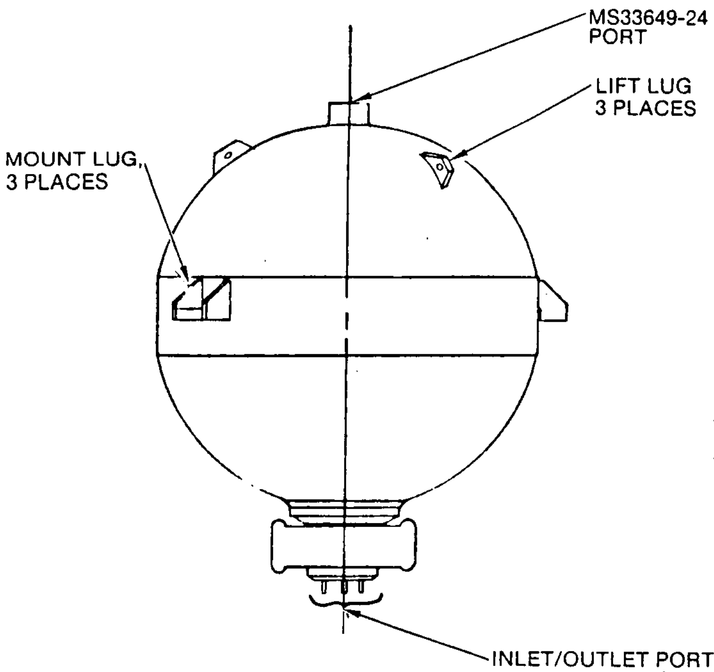


Figure 3-11. Oxygen Valve Panel

The accumulator tanks were standard ASME coded vessels with a 4-to-1 safety factor fabricated by Capital Westward Company for the test bed. The tank contained propellants for approximately 830 s of engine firing time (22,600 lb-s). Figure 3-12 summarizes the accumulator tank design.

The system was provided with sufficient instrumentation to ensure safe operations as well as obtain diagnostic data.

All soft goods (O-rings, valve seats, etc.) used in the components and system were impact batch tested to Space Shuttle Main Engine (SSME) specification to preclude ignition and burning during testing.



	H_2	O_2
TANK ID (in)	42	26
VOLUME (ft^3)	22.45	5.33
WEIGHT (lb)	3050 lb	750 lb
MAX OPERATING PRESSURE (psi)	1,500	1,800

$$\left.\begin{array}{l} I_{TOTAL} \\ MR = 4 \\ T_o = 380\ °R \\ T_f = 300\ °R \\ P_{NOM} = 1{,}000\ psi \\ P_{MIN} = 200\ psi \end{array}\right\} \quad 22{,}600\ lb\text{-}s$$

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Figure 3-12. Accumulator Tanks (ASME Coded)

3.2 TEST BED CONTROLLER DESIGN SUMMARY

In keeping with the concept of supplying MSFC with a complete stand-alone test bed, an integrated control and data acquisition system was included. The design goals specified a system that would exercise overall control of test bed operations with a maximum amount of automation, demonstrated safety, and high reliability. Test bed operation was similar to that required on the space station, but with a high degree of flexibility necessary for a test development program. Computer control systems with these characteristics have been used at the Rocketdyne Santa Susana Field Laboratory (SSFL) for over 10 years, and it was decided to use the basic concepts and techniques developed for them as a design basis for the test bed system.

The systems, centered around minicomputers and associated components, acquire engineering data while controlling valves, monitoring parameter limits and events, and completely controlling the test sequence. To perform these integrated operations, specialized software was written including a high order computer language called Rocketdyne Test Control Language (RTCL). The software system and concepts were also implemented in the SNIA BPD test facility in Colleferro, Italy in 1981, and at the Air Force Weapons Laboratory in 1982.

In recent years, many of the test facilities at Rocketdyne have had the RTCL software implemented in Data General computer hardware; and this led to the selection of a Data General Desktop Model 30 as the microprocessor utilized for the test bed.

The control system was composed of a manual control panel, the microprocessor, and its various ancillary components and signal conditioning equipment (Figure 3-13 and Table 3-3). All of the components were assembled into a compact desk arrangement (Figure 3-14) which was located in the control center about 500 ft from the test cell.

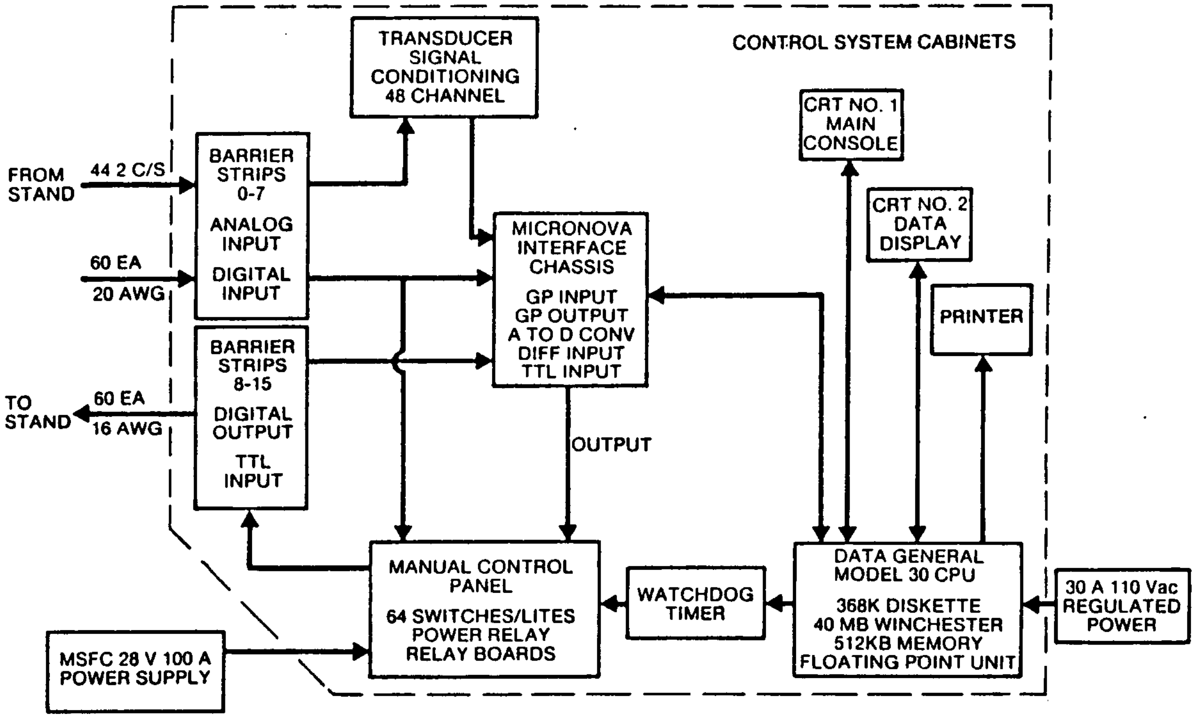

Figure 3-13. Computer Control System Block Diagram

Table 3-3. Microprocessor Hardware Configuration

Microprocessor is a Data General Desktop Model 30 with the following features:

- 512-KB semiconductor memory with byte parity
- Hardware floating point unit
- 368-KB diskette unit
- 40-MB winchester hard disk
- Two 123-W power supplies
- Digital-to-analog converter
- Differential multiplexer
- 64 digital 28-Vdc outputs (optoisolated)
- 64 digital inputs (optoisolated)
- Printer
- CRT display for 24 channels of engineering unit data
- CRT terminal for operating interface

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Figure 3-14. Test Bed Control System

When power was initially applied, control of all devices was from the manual panel. When automatic control was desired, a momentary switch shifts power to the computer. Control remains with the computer until a reset circuit is actuated either manually or from the "watchdog timer."

The "watchdog" is a Rocketdyne built device that monitors timing signals from three of the primary programs in the control software. If any of the programs failed to signal within a set cycle time, control automatically returned to the manual panel. In this way failure of the computer system could be detected, and by means of presetting manual switches the test bed could be returned to a safe condition.

A block diagram of the system is shown in Figure 3-15.

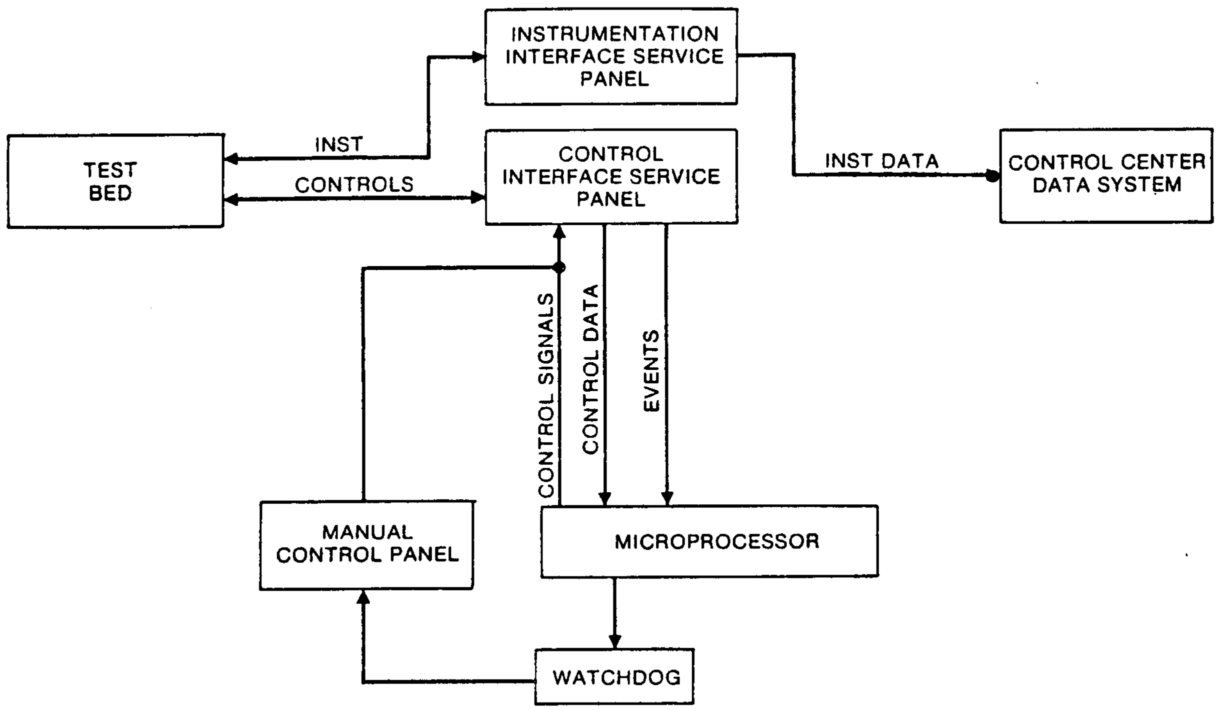


Figure 3-15. Control System Block Diagram

The RTCL implemented in the test bed is a very flexible and powerful high order programming language consisting of 38 basic commands with up to 4 variables associated with each. Table 3-4 describes the primary features.

The event data were recorded on the hard disk every 20 msec and the parameter data were recorded every 100 msec. Off-line programs were available to reduce the data to engineering units and to produce a time line of all of the events that occurred.

The mass flow rate of the main propellants was calculated by using pressure and temperature upstream of the sonic venturi and could be controlled by comparing the calculated values to desired values and making necessary pressure corrections. The pressure upstream of the venturis was controlled by simple regulators. The reference pressures of the regulators were controlled by the computer to maintain the flow rate between upper and lower limits.

Table 3-4. RTCL Features

• Monitors 64 valve positions every 100 msec
• Controls sequence of 64 output signals on 1 msec basis
• Monitors 128 limits on raw or calculated data each 100 msec
• Performs corrective action or terminates for limits
• Uses flags, counters, and other branch statements for flexible sequence
• Emulates "expert systems"

To connect the control system to the test bed, an interface box was used. All control transducers and valves on the bed were wired to this interface box. Because MSFC maintains strict separation of control and data acquisition functions, a second interface box was provided for the diagnostic data.

MSFC personnel wired from terminals strips in the two boxes, through bulkhead connectors in the cell wall, and from there to the control center and recording center (Figure 3-16). The diagnostic data signals were conditioned and digitized in the test cell area prior to being transmitted approximately 1,000 ft to the recording center. Digital displays of engineering unit data were provided in the control center during a test and printouts of engineering unit data and plots of data were produced shortly after completion of a test.

3.3 CRYOGENIC SUPERCRITICAL STORAGE MODULE DESIGN SUMMARY

The initial design of the test bed included cyrogenic oxygen and hydrogen storage tanks operating at supercritical pressures. These tanks were to simulate the station central propellant storage modules. In operation, the central propellant storage tanks would be maintained at or just below the tank vent pressures by heat supplied from internal tank heaters. The accumulators would be slowly charged to their operating level from the central supply

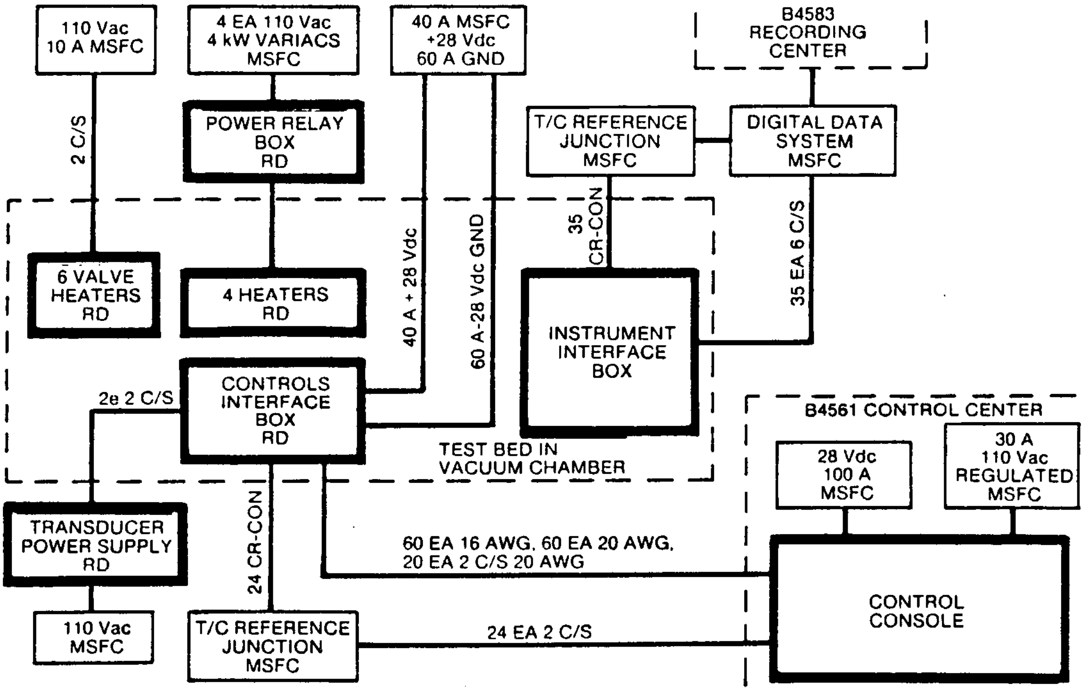


Figure 3-16. Design Overview Interfaces

source. The propellants would be passed through in-line heaters between the storage module and accumulators raising the now gaseous propellant temperature. Upon command from the space station guidance, navigation and control system, the thrusters would be commanded to fire using propellants supplied from the accumulators. After completion of the thruster operation, the accumulators would be replenished slowly from the central propellant storage system.

The design of the O_2 and H_2 storage vessels was performed under contract by Beechcraft. This effort consisted of the thermal analysis, heater analysis, structural analysis, and development of the design drawings of the oxygen and hydrogen storage vessels for the test bed.

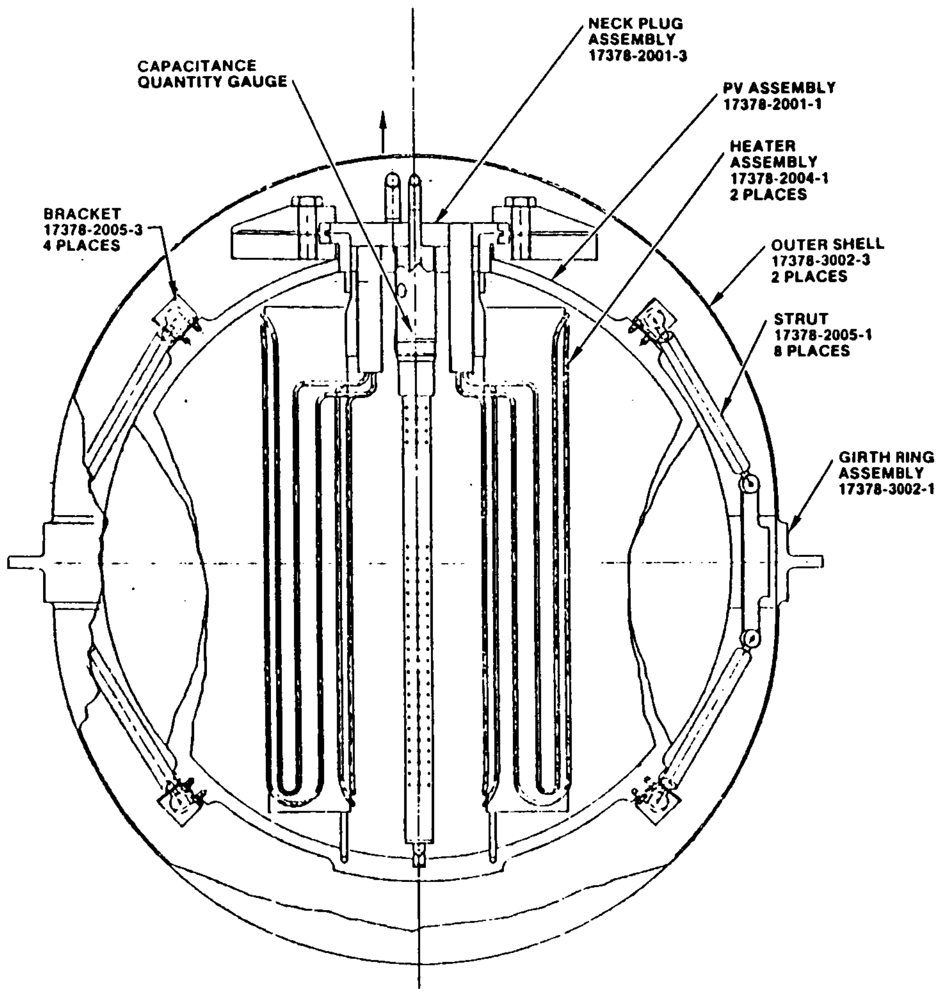
The oxygen storage vessel was a 26 in. ID 304L stainless steel sphere designed for a maximum operating pressure of 1,500 psia. The hydrogen storage tank was a 42 in. ID 316L stainless steel sphere designed for a maximum pressure of

1,100 psia. These pressure vessels were each encased in a 6061 Al vacuum jacket. The tanks contained a quantity gaging system and an electrical heater. The specifications for these vessels are presented in Table 3-5 and Figure 3-17 displays the final design concept as prepared for the test bed program.

The thermal analysis considered heat leakage, the cool down and fill operation, Dewar performance after fill, Dewar performance during test, and vent line sizing to minimize radiation heat losses. The oxygen tank utilized 9 layers of double Al-mylar/nylon blankets and the hydrogen tank utilized 30 layers. The maximum heat leakage, considering both radiation and conduction, was determined to be 33 Btu/h for the oxygen tank and 21 Btu/h for the hydrogen tank. A detailed heat leakage summary is presented in Table 3-6.

Table 3-5. Propulsion Test Bed Cryo System Specifications

REQUIREMENT	OXYGEN	HYDROGEN
SYSTEM		
MAX NORMAL OPERATING PRESSURE (PSIA)	1300	1000
MAX DESIGN PRESSURE (PSIA)	1500	1100
MIN OPERATING PRESSURE (PSIA)	750	200
MIN FLOW RATE (LBM/HR)	45.2	15.2
HANDLING LOADS VERT/HORIZ (G's)	3/1.5	3/1.5
HEAT LEAK (BTU/HR)	33	21
HOLD TIME, 10% ULLAGE (HRS)	232	219
FILL TIME (HRS)	0.9	0.8
PRESSURE VESSEL		
PRESSURE VESSEL ID (IN)	26	42
VOLUME (FT^3)	5.33	22.45
CAPACITY (LBM)	378	104
PV MATERIAL	304L	316L
PV WEIGHT DRY (LBM)	450	1350
OUTER SHELL		
VACUUM JACKET ID (IN)	31	50
MAX ENVELOPE (IN)	35	54
VACUUM JACKET MATERIAL	6061 AL	6061 AL
HEATERS		
EFFECTIVE SURFACE AREA EACH (IN^2)	270	457
TOTAL WATTAGE (WATTS)	2000	4000
OPERATING VOLTAGE (VAC)	65	111
LIMIT TEMPERATURE (°F)	350	200



SPECIFICATIONS		
PARAMETER	H_2	O_2
PV DIAMETER ID (in.)	42	26
MAXIMUM OPERATING PRESSURE (psia)	1100	1500
DESIGN PRESSURE (psia)	750	1000
TEMPERATURE (°R)	40	160
CAPACITY (lb)	104	378
DOUBLE SHEATH HEATER (kW)	4	2
PV MATERIAL	316L	304L
VACUUM JACKET ID (in.)	50	31
MAXIMUM ENVELOPE (in.)	54	35

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Figure 3-17. Supply Tank Design Summary

Table 3-6. Heat Leak Summary

	OXYGEN DEWAR @ 1300 PSI		HYDROGEN DEWAR @ 1000 PSIA	
	MAXIMUM (BTU/HR)	AVERAGE (BTU/HR)	MAXIMUM (BTU/HR)	AVERAGE (BTU/HR)
I. CONDUCTION				
SUPPORT STRUTS	.7	.5	.8	.7
PLUMBING (FILL, VENT)	.9	.7	.6	.5
INST. AND HEATER WIRE CONDUIT	.5	.4	.4	.4
HEATER WIRE (20 AWG)	2	1	2	1
TOTAL	~4	~3	~4	~3
II. RADIATION				
(9 LAYERS O_2, 30 LAYERS H_2 DOUBLE AL-MYLAR/NYLON BLANKET)	~ 29	~ 22	~ 17	~ 15
TOTAL HEAT LEAK	~ 33	~ 25	~ 21	~ 18

The cool down and the fill time was determined to be 0.9 h for the oxygen tank and 0.8 h for the hydrogen tank. The calculations for the hydrogen tank were made using a fill rate of 125 lb/h and loading for fill at a temperature of 34°R and a pressure of 14.7 psia. The calculations for the oxygen tank were made using a fill rate of 250 lb/h and loading for fill at a temperature of 160°R and a pressure of 14.7 psia. The fill and cool down characteristics of the two tanks are shown graphically in Figures 3-18 and 3-19.

The postfill performance for the Dewars was determined for the case where the tanks were loaded with 1% and 10% ullage volume. In the case of the 1% ullage, it was found that the hydrogen could be held for 142 h before the vent pressure of 1,100 psia was reached and 65 h before the oxygen reached the vent pressure of 1,500 psia. When the ullage was increased to 10%, the holding time for the hydrogen was extended to 232 h and to 219 h for the oxygen tank. Graphic presentations of postfill performance are presented in Figure 3-20.

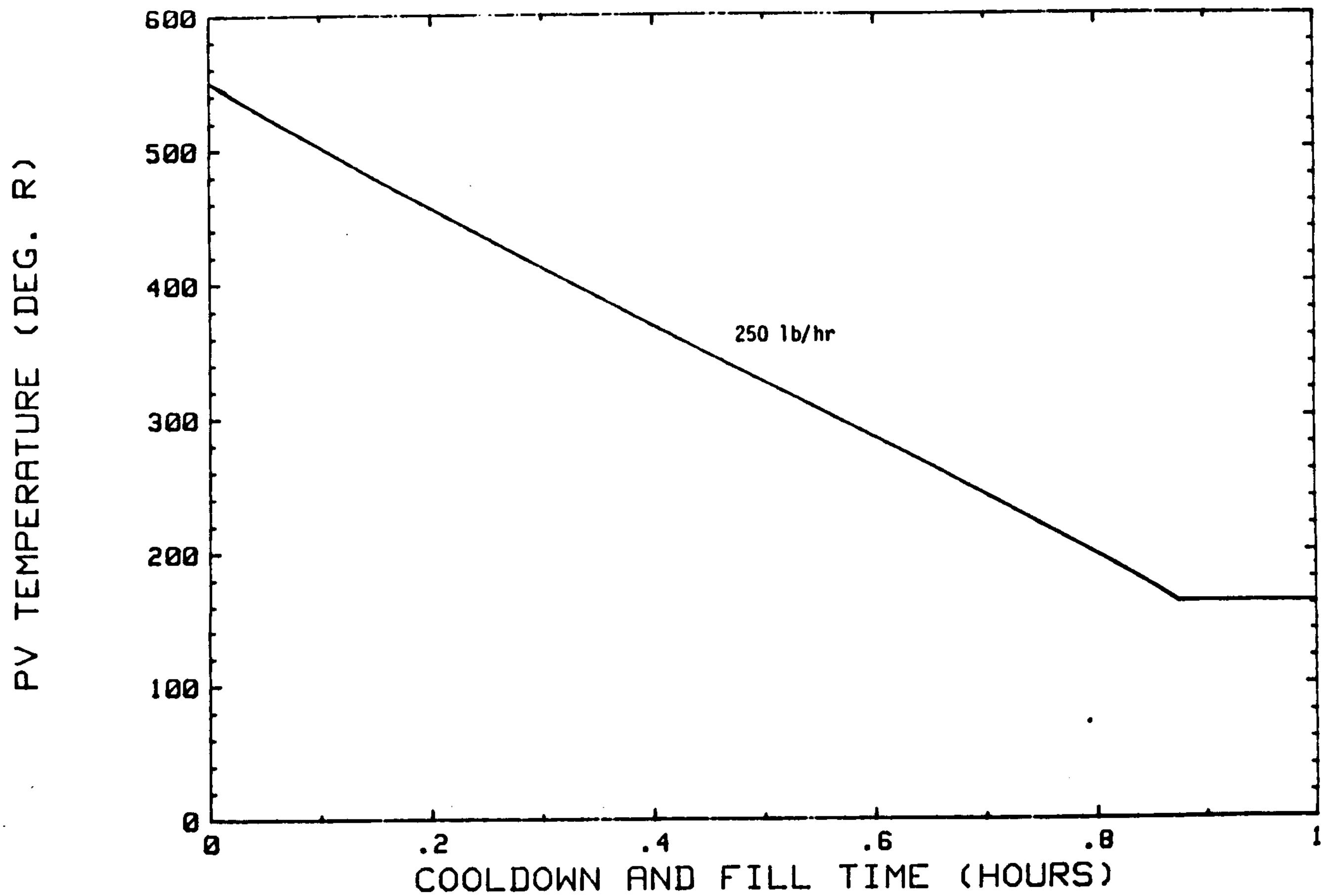


Figure 3-18. O_2 Dewar Cool Down and Fill Time for Fill at T = 160°R; P = 14.7 psia

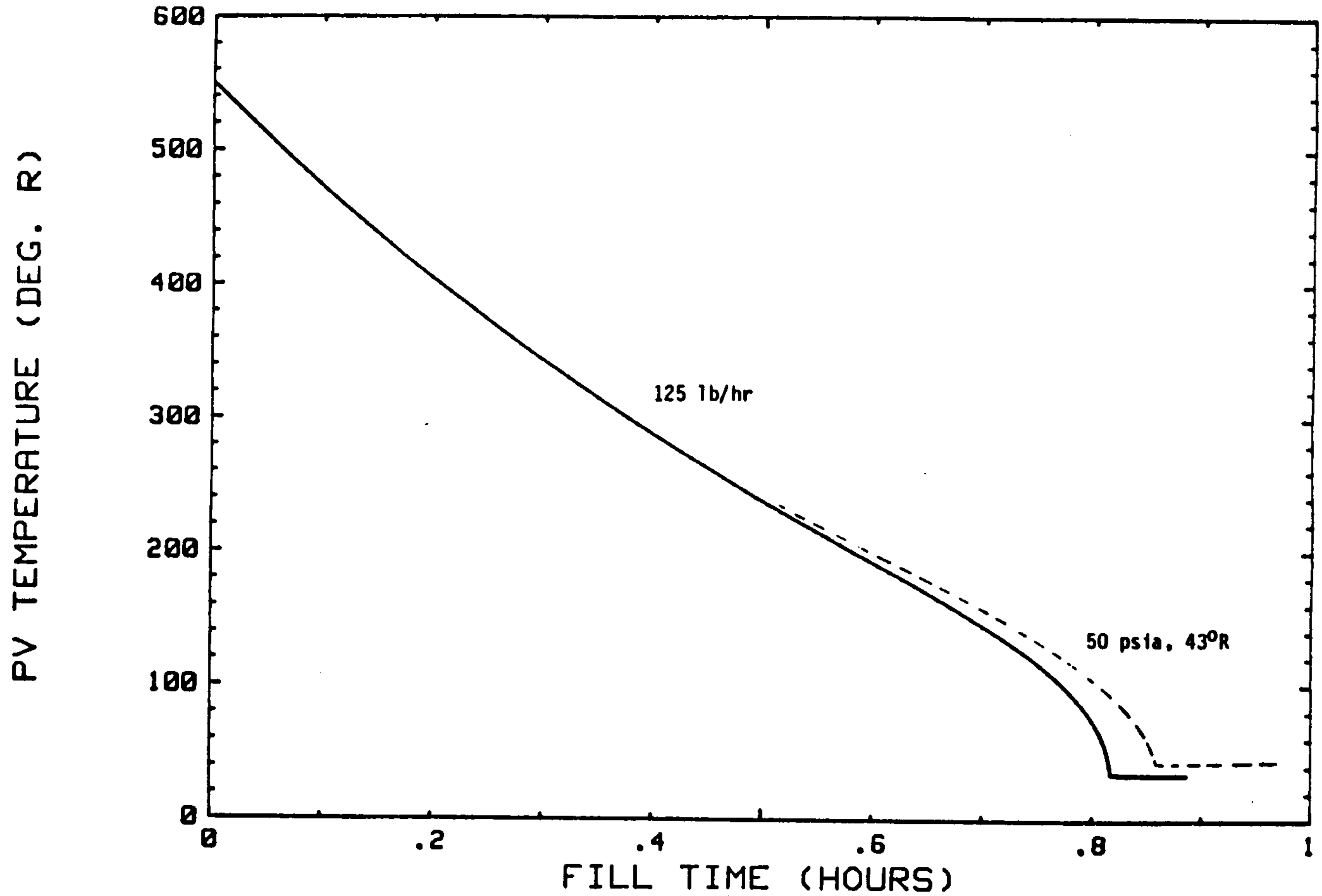


Figure 3-19. H_2 Dewar Cool Down and Fill Time for Fill at T = 34°R; P = 14.7 psia

PRE-TEST HOLD:

- VENTING NOT PERMITTED FOR MINIMUM OF 48 HOURS
- INITIAL PRESSURE = 40 PSIA
- PRESSURIZATION VIA HEAT LEAK: INITIAL PRESSURE — VENT PRESSURE

	H_2 DEWAR	O_2 DEWAR
ULLAGE	1%	1%
VENT PRESSURE	1100 PSIA	1500 PSIA
PRESSURIZATION ENERGY	2380 BTU	2330 BTU
PRESSURIZATION (HOLD) TIME	142 HRS	65 HRS

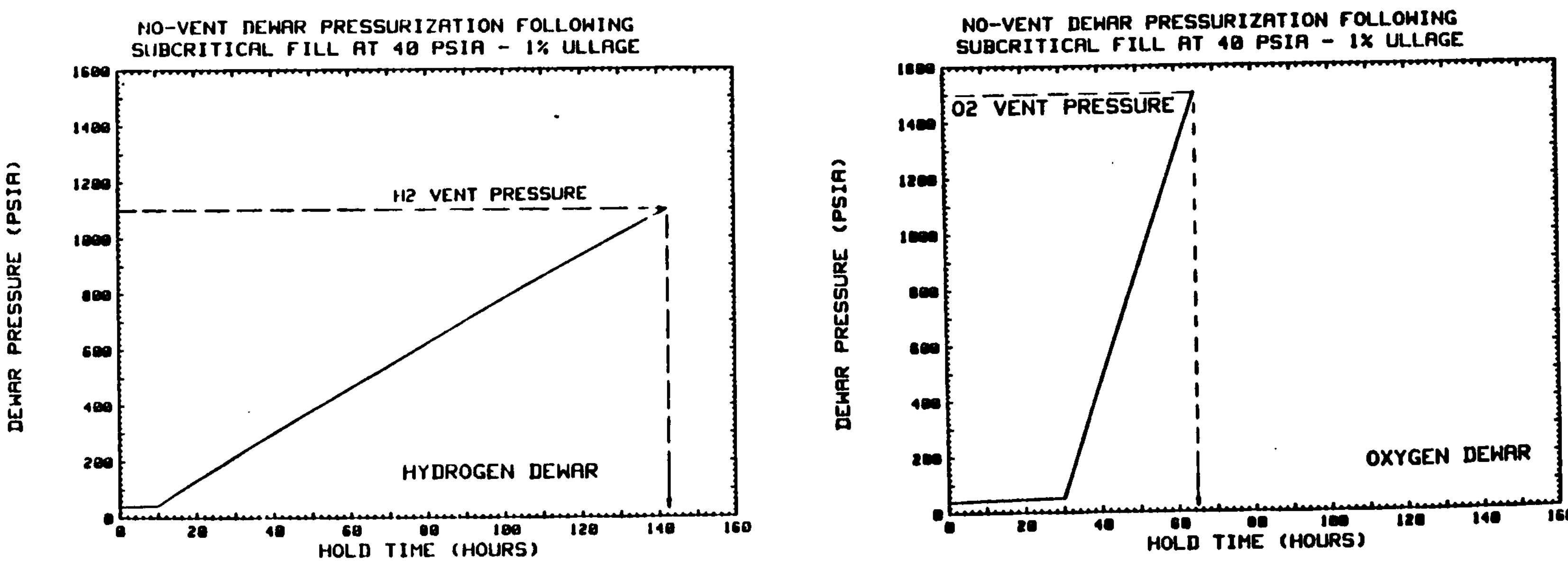


Figure 3-20. Dewar Performance After Fill (Sheet 1 of 2)

LONG-TERM HOLD:
- VENTING NOT PERMITTED FOR MINIMUM OF 200 HOURS
- MAXIMUM 10% ULLAGE

	H_2 DEWAR	O_2 DEWAR
ULLAGE	10%	10%
VENT PRESSURE	1100 PSIA	1500 PSIA
PRESSURIZATION ENERGY	4820 BTU	7130 BTU
PRESSURIZATION (HOLD) TIME	232 HRS	219 HRS

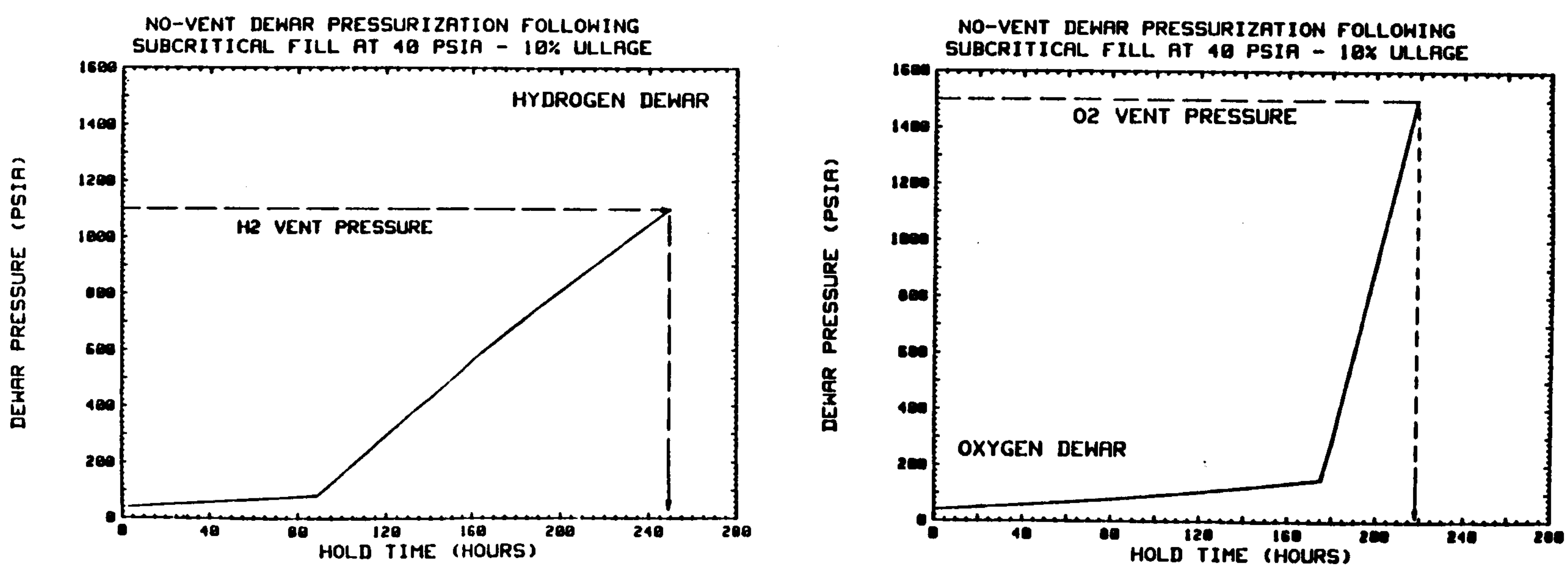


Figure 3-20. Dewar Performance After Fill (Sheet 2 of 2)

The vent line OD of 0.625 in. was determined by considering that the line diameter must be sufficient to prevent pressure increase in case of annulus vacuum loss. The analysis is based on the thermally worst case, where the heat transfer to the fully loaded hydrogen Dewar was by air condensing on the pressure vessel and vent line. It was determined that the hydrogen was the worst case. The same diameter tubing was used for the oxygen vent system for commonality.

The Dewars were to supply propellants to the accumulators. After the tanks had been cooled down and filled, they are brought up to the operating pressure by isolating the Dewars and heating the propellants with the electric heaters installed inside the pressure vessels. After the accumulators have been charged, the accumulators are again isolated and the pressure increased to the vent pressure level by heating the propellants with the heaters. As the propellants in the Dewars are depleted, more power is required to achieve the vent pressure level. In the case of hydrogen, the energy to achieve the pressurization level of 1,100 psia after the first accumulator fill is 3,010 Btu, and after the fifth fill had increased to 11,300 Btu. For oxygen, the energy required to raise the vent pressure to 1,500 psia after the first accumulator fill was 1,150 Btu. This increased to 5,760 Btu after the fifth fill. The Dewar performance during testing is presented graphically in Figure 3-21.

The heaters were designed for use in a 2-g environment. The calculated heater surface area was increased by 50% to provide adequate safety margin. The worst case condition for the heat absorption capability of the propellants (i.e., low density, high temperature fluids and maximum allowable heater temperature) was used for the heater design. The summation of the radiation heat transfer from the heater to the propellant was determined using the same correlation used in the shuttle PRSA heater analysis.

The convection heat transfer from the heater to the fluid occurs both inside and outside of the heater tube. This is shown pictorially with the relationships for determining the internal and external free convection heat transfer in Figure 3-22.

HOLD TIME BETWEEN ACCUMULATOR REFILLS: VENTING NOT PERMITTED BETWEEN REFILLS

- INITIAL PRESSURE ≈ CRITICAL PRESSURE OF FLUID
- 1% ULLAGE AT FILL ASSUMED (HOLD TIME INCREASES WITH INCREASED ULLAGE)

	H_2 DEWAR		O_2 DEWAR	
	1ST-2ND	5TH-6TH	1ST-2ND	5TH-6TH
VENT PRESSURE	1100 PSIA	1100 PSIA	1500 PSIA	1500 PSIA
PRESSURIZATION ENERGY	3010 BTU	11300 BTU	1150 BTU	5760 BTU
PRESSURIZATION (HOLD) TIME	146 HRS	557 HRS	37 HRS	205 HRS

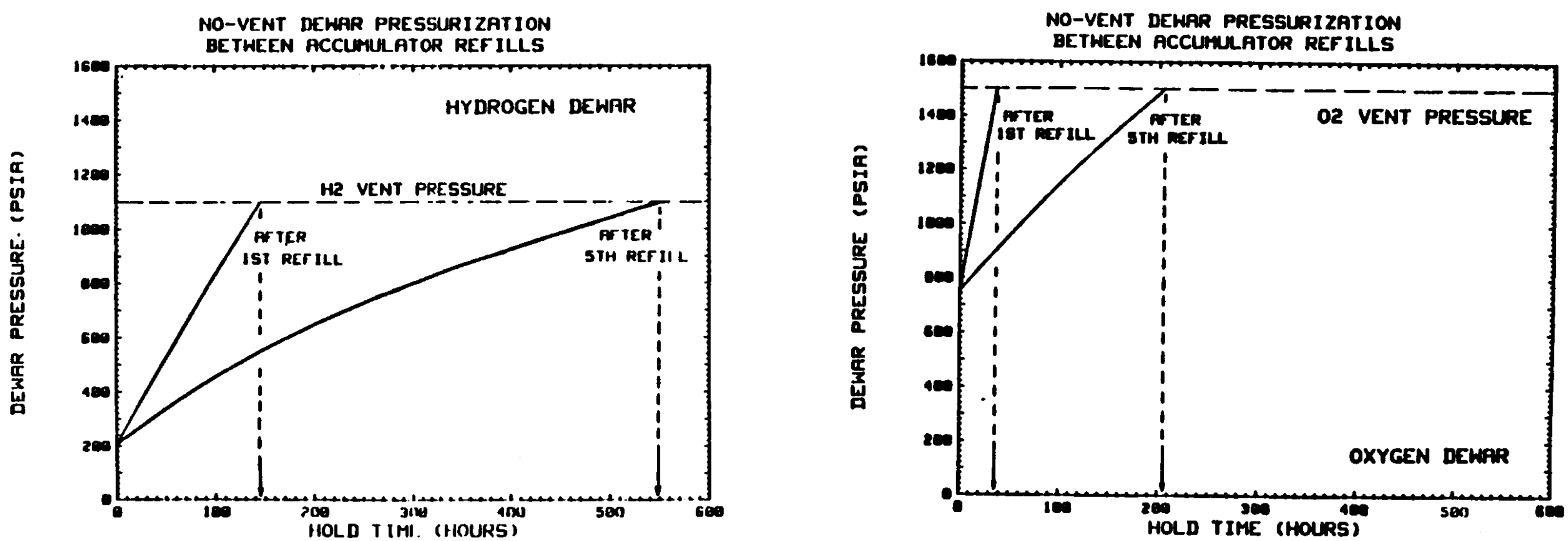
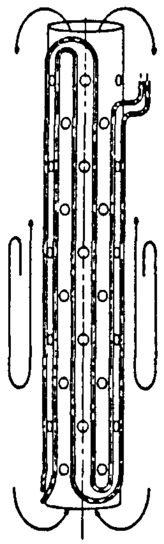


Figure 3-21. Dewar Performance During Testing

o FREE CONVECTION
EXTERNAL SURFACE:



$Q = \bar{h}_c A (T_H - T_M)$

WHERE:
- Q = FREE CONVECTION HEAT TRANSFER (BTU/Hr)
- A = HTR ELEMENT SURFACE AREA EXTERNAL (Ft^2)
- T_H = HEATER TEMPERATURE (R)
- T_M = MEAN FLUID TEMP OUTSIDE (R) = $(T_H + T_{FLUID})/2$
- $\bar{h}_c$ = AVG UNIT CONVECTIVE CONDUCTANCE ($BTU/HrFt^2R$)

$\bar{h}_c = 0.548\ K/L\ (GR \bullet PR)^{0.25}$

WHERE:
- K = THERMAL CONDUCTIVITY OF FLUID (BTU/HrFtR)
- L = CYLINDER LENGTH (Ft)
- GR = GRASHOF NUMBER (-)
- PR = PRANDTL NUMBER (-)

$GR = \rho^2 g_c \beta (T_H - T_M) L^3/\mu^2$

WHERE:
- ρ = FLUID DENSITY (Lbm/Ft^3)
- g_c = GRAVITATIONAL CONSTANT = 32.174 (Ft/sec^2)
- β = TEMP COEFFICIENT OF VOLUME EXPANSION (1/R)
- μ = ABSOLUTE FLUID VISCOSITY (Lbm/Ft-sec)

o FREE CONVECTION
INTERNAL SURFACE:

$\bar{h}_c = 1.962\ (K^2 \rho^2 \beta C_p g_c (T_H - T_M)/\mu)^{0.333}$

WHERE:
- C_p = FLUID SPECIFIC HEAT (BTU/LbmR)
- T_M = MEAN FLUID TEMP INSIDE (R) = $(.75T_H + .25\ T_{FLUID})$

Figure 3-22. Heat Transfer Mechanisms in a 1-g Environment

Using the above referenced relationships, it was determined that the hydrogen heater required an external surface area of 914 in^2 with 4,000 W power and that the oxygen heater required an external area of 540 in^2 with 2,000 W power. A summary of the components of the heater is presented in Table 3-7.

These heater configurations give a hydrogen heater temperature of 200°F and a fluid temperature of 160°F at 1,100 psia pressure and an oxygen heater temperature of 3500°F at 1,300 psia pressure.

Of concern from the standpoint of safety is the maintenance of the oxygen heater sheath temperature below the autoignition temperature of the sheath material. The maximum temperature occurred in the splice of the power lead to the heater conductor. The temperature profile in this critical area was well below the autoignition temperature for the 300 series corrosion-resistant steel.

Table 3-7. Heater Surface Area Summary

PARAMETER		O_2	H_2
CYLINDER LENGTH	(IN)	22	38
CYLINDER DIAMETER	(IN)	3.5	3.5
NUMBER OF HOLES		60	96
HOLE DIAMETER	(IN)	0.5	0.5
HEATER WIRE LENGTH	(IN)	137	197
HEATER WIRE DIAMETER	(IN)	.187	.187
CYLINDER AREA - EXT	(IN^2)	241.9	417.8
HOLE AREA	(IN^2)	-11.8	-18.8
WIRE SRFC AREA (1/2)	(IN^2)	40.2	57.9
EXTERNAL HTR AREA	(IN^2)	270	457
NUMBER OF HEATERS		2	2
TOTAL EXTERNAL AREA	(IN^2)	540	914

As the propellant is depleted from the Dewars, their lesser density results in a change in their specific heat. In order to maintain constant storage conditions with a constant heater input a varying mass flow rate results. The effect of fluid density is depicted graphically in Figure 3-23. Using these data for a constant hydrogen heater of 4000 Watts, the time required to deplete the usable mass of hydrogen of 83.1 lbm was determined to be 2.3 h; and with a constant oxygen heater input of 2000 W, depletion of the usable fluid mass of 324.9 lbm was accomplished in 3.7 h. The influence of various heater power levels is shown in Figure 3-24. A summary of the heater requirements resulting from the above analyses is presented in Table 3-8.

Structural analysis was performed on the oxygen and hydrogen pressure vessels, outer shells, support struts, strut fixtures, fill and vent lines, neck plug, and the pressure vessels to ensure compliance with transportation and in use loadings.

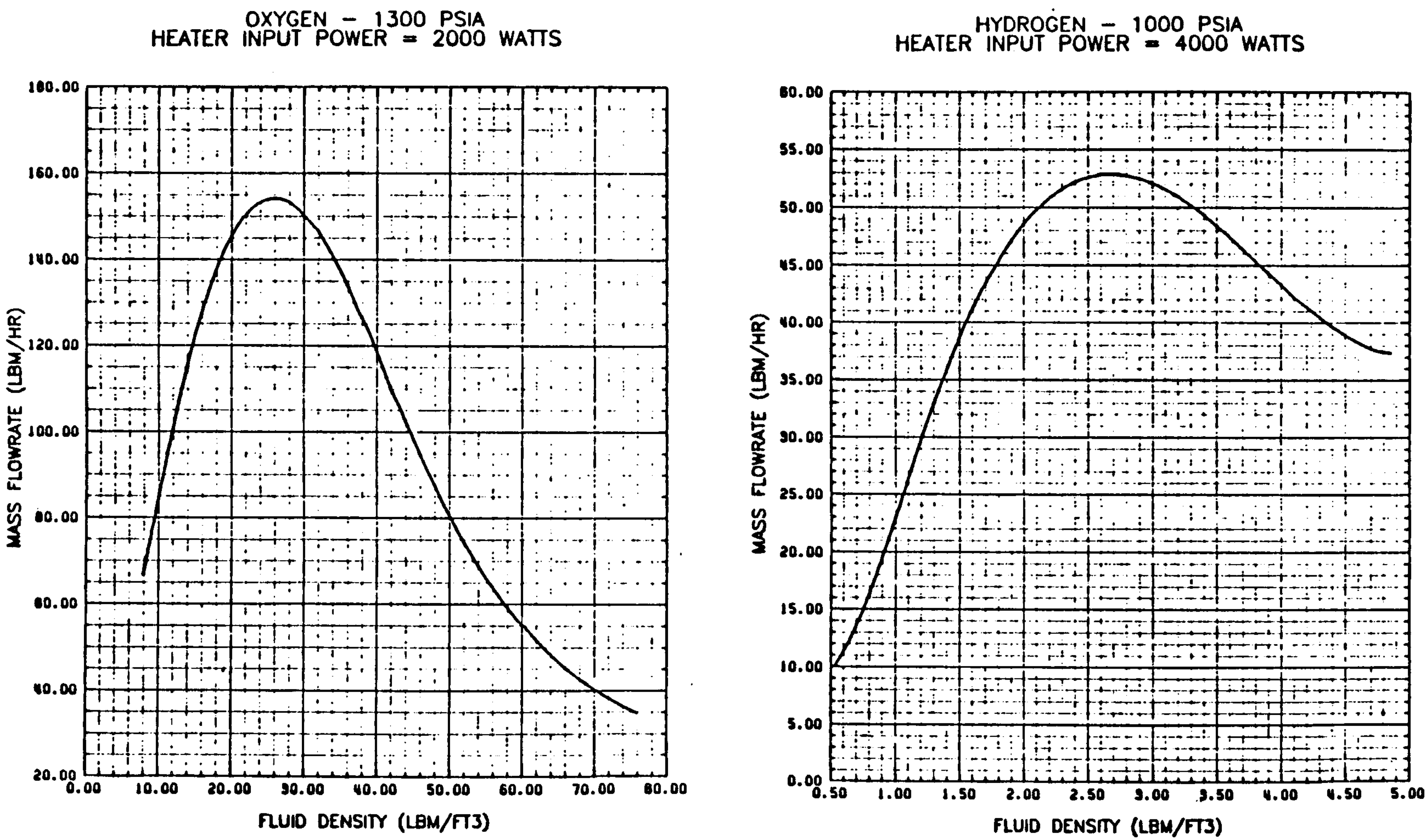


Figure 3-23. Mass Flow Rate Versus Fluid Density for Constant Heater Power Input

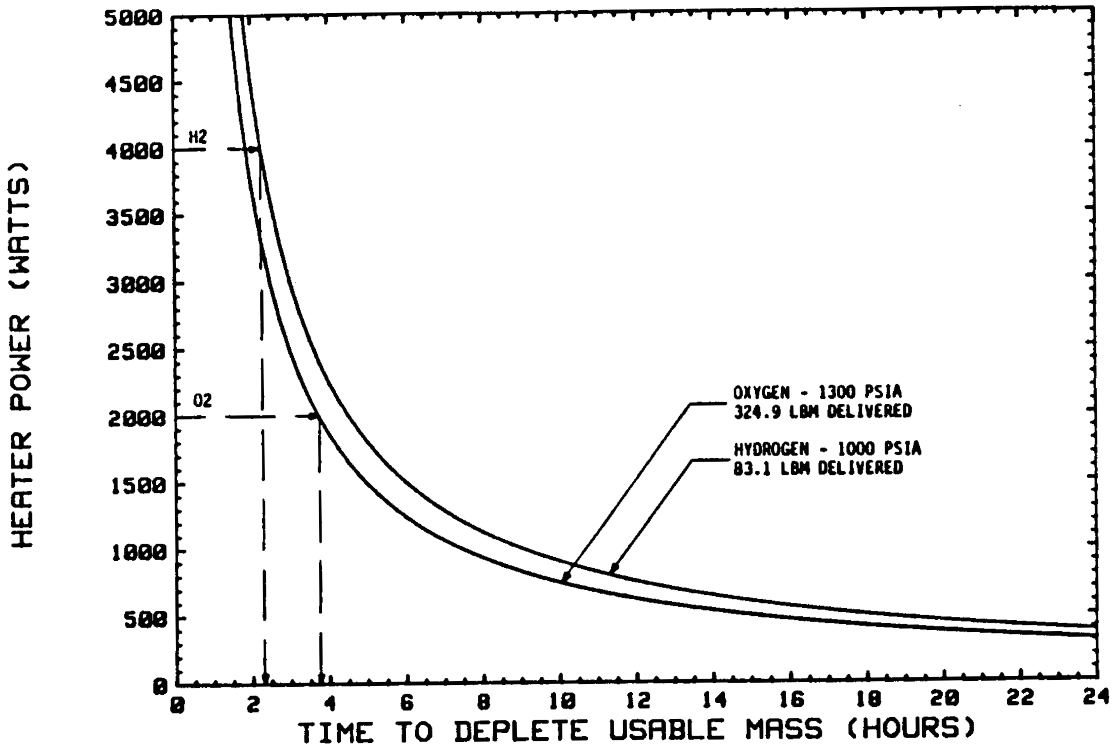


Figure 3-24. Time Required to Deplete Usable Mass

Table 3-8. Summary of Heater Requirements

	O_2 1300 PSIA	H_2 1000 PSIA
DEWAR VOLUME (FT^3)	5.3	22.5
LOADED FLUID DENSITY (LBM/FT^3)	69.5	4.3
FLUID TEMP LIMIT (°R)	490	300
INITIAL FLUID MASS (LBM)	370.4	96.5
RESIDUAL MASS (LBM) AT TEMP LIMIT	45.5	13.4
USABLE FLUID MASS (LBM)	324.9	83.1
LBM/ACCUMULATOR FILL	48	12
NO. OF FILLS/DEWAR	6.8	6.9
ENERGY REQUIRED TO DEPLETE USABLE MASS (W-HRS)	7456	9008
HEATER POWER (W)	2000	4000
TIME TO DEPLETE USABLE MASS (HRS)	3.7	2.3
INTEGRATED AVERAGE FLOWRATE (LBM/HR)	87.8	36.1
MINIMUM HEATER SURFACE AREA REQUIRED (IN^2)	505	490

3.4 ELECTROLYSIS MODULE DESIGN SUMMARY

The electrolysis module was designed as an integrated package of electrolysis units, gas dryers, propellant storage tanks, and associated valves and controls. The water, nitrogen purges, and pressurization were facility supplied. Drawing 7R032825, included as part of the design drawing package in Appendix A, displays a complete schematic of the test bed including the electrolysis system. Drawing 7R032840, Appendix A, depicts the electrolysis module assembly.

The pallet assembly was simply a structural base providing mounting lugs, cradles and support for the module components. Fabricated from channel, it provided a rigid base for transport and handling and a means of attachment to the top of the propulsion module.

The propellant storage tanks were three filament wrapped vessels provided by SCI and two metallic tanks supplied by Arde Inc. The three SCI tanks used were cylindrical with hemispherical ends and were fabricated using a spun seamless 6061 aluminum liner overwrapped with a high strength graphite fiber filament-wound/resin structure. The tanks were 20.2 in. in diameter and 78 in. in length.

The two Arde steel tanks were 23 in. diameter spheres fabricated from 301 cryoformed stainless steel. The tanks used were considered representative of composite and metal tanks that could be used for the space station application.

The canisters contained the electrolysis units. The electrolysis prototype units were not designed for operation in the vacuum test environment used for the test bed. The canister for the HSD unit (7R032829 Appendix A) was designed to permit operation of the electrolysis components at standard atmospheric pressure. The LSI electrolysis components were designed to operate at a maximum output pressure of 350 psi at standard atmospheric conditions. The LSI containment canister was designed to contain pressures up to 1,250 psig. This approach permitted the output supply pressure of the electrolysis

products to be increased to 1,000 psi or more by simply increasing the ambient pressure environment of the electrolysis unit to maintain required pressure differentials across electrolysis components.

Molecular-sieve dryers designed by Boeing and fabricated at MSFC were included in the module. Each dryer was furnished with electrical resistance heaters to expel moisture collected from the electrolysis effluent during a vacuum drying/heating cycle. Dual dryer/heater assemblies were used in both the hydrogen and oxygen supply systems. By alternating between the two dryers, continuous electrolysis system operation was possible. After operation for a time sufficient to saturate a dryer with water, a control system would switch operation to the second dryer, turn on the heater for the first dryer and vent it to vacuum for drying.

Moisture sensors were used to monitor the effluent water content to determine the point of dryer saturation and the need for switching to operation with the second dryer and to initiate vacuum drying of the first.

There were two basic types of electrolysis units considered for test on the test bed as applicable for future space station use. A system using an alkaline (KOH) electrolyte is being developed by LSI. A system using a solid polymer acidic electrolyte is being developed by United Technologies HSD.

LSI's static feed electrolyzer (SFE) concept uses a vapor-fed cell with a fibrous matrix separator and a system that promises operation without active cooling. The SFE cell concept tested is shown in Figure 3-25. It evaporates water from an internal water-fed cavity and feeds the vapor to the cell electrodes. The potassium hydroxide electrolyte is held in a fibrous matrix between the electrodes. The cooling was done by pumping the fluid in the water feed cavity through a coolant loop.

The SFE cell has shown to be capable of operating at optimized current densities without coolant and present developments are investigating the elimination of the coolant loop entirely in favor of direct passive conduction

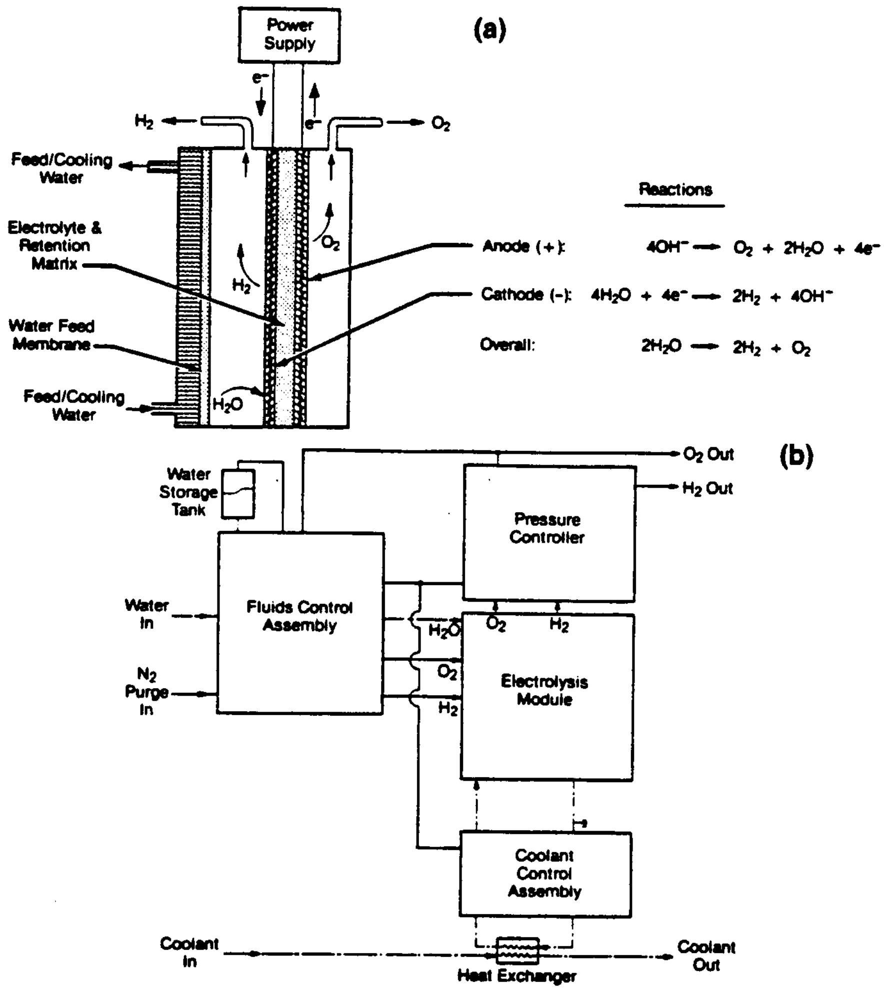


Figure 3-25. SFE with Coolant Circulation (a) Electrolysis Process (b) Subsystem Functional Block Diagram

radiation cooling. The SFE concept without cooling has only four components; the electrolyzer cell stack, a pressure controller, a fluid controller, and a water tank.

The HSD unit tested during the program was a conductively cooled module with static vapor water feed to the electrolysis cell. This design eliminates the need for any water pumps or phase separators. An alternative is the anode feed concept used for submarine electrolysis units. This approach circulates the reaction (and cooling) water through the anode chamber of the cells (anode

feed) using pumps. The effluent oxygen and hydrogen have to be separated from the liquid water at the outlet of the module by the use of phase separators. The anode feed design will provide higher efficiencies, lower weight, and smaller volume than the solid polymer static feed system. Excess heat from the module would be rejected through heat exchanger rather than a cold plate as used for the static-feed system.

A comparison of the characteristics of the alkaline (LSI) and solid polymer acid (HSD) systems is given in Table 3-9. The high efficiency of the alkaline system would result in a space station system with low power consumptions and probably no active cooling requirements. Critical control of operating parameters would be required to prevent contamination of the system with the KOH electrolyte. The acid solid polymer electrolyte (SPE) system electrolysis

Table 3-9. Technical Comparison of Electrolysis Options

Option	Advantages	Disadvantages
Alkaline Electrolysis	High Efficiency Low power required Extensive single cell data base Alkaline fuel cells on Apollo, Shuttle Depressed dewpoint output gas	Limited stack data base Limited high pressure data KOH contamination possible
Acid Electrolysis		
SPE anode-feed	Extensive data base High pressure in field, submarine service	High power required Low efficiency Saturated output gas Pump/separation required Deionizer required Heat rejection system
SPE static cathode-feed	No pump/separators required No deionizer required	Lowest efficiency Highest power required Saturated output gas Limited data base, high pressure Heat rejection

cell would be very rugged and durable but would require an active cooling system; additional components in the form of pumps, separators, and dryers; and would have high power supply needs.

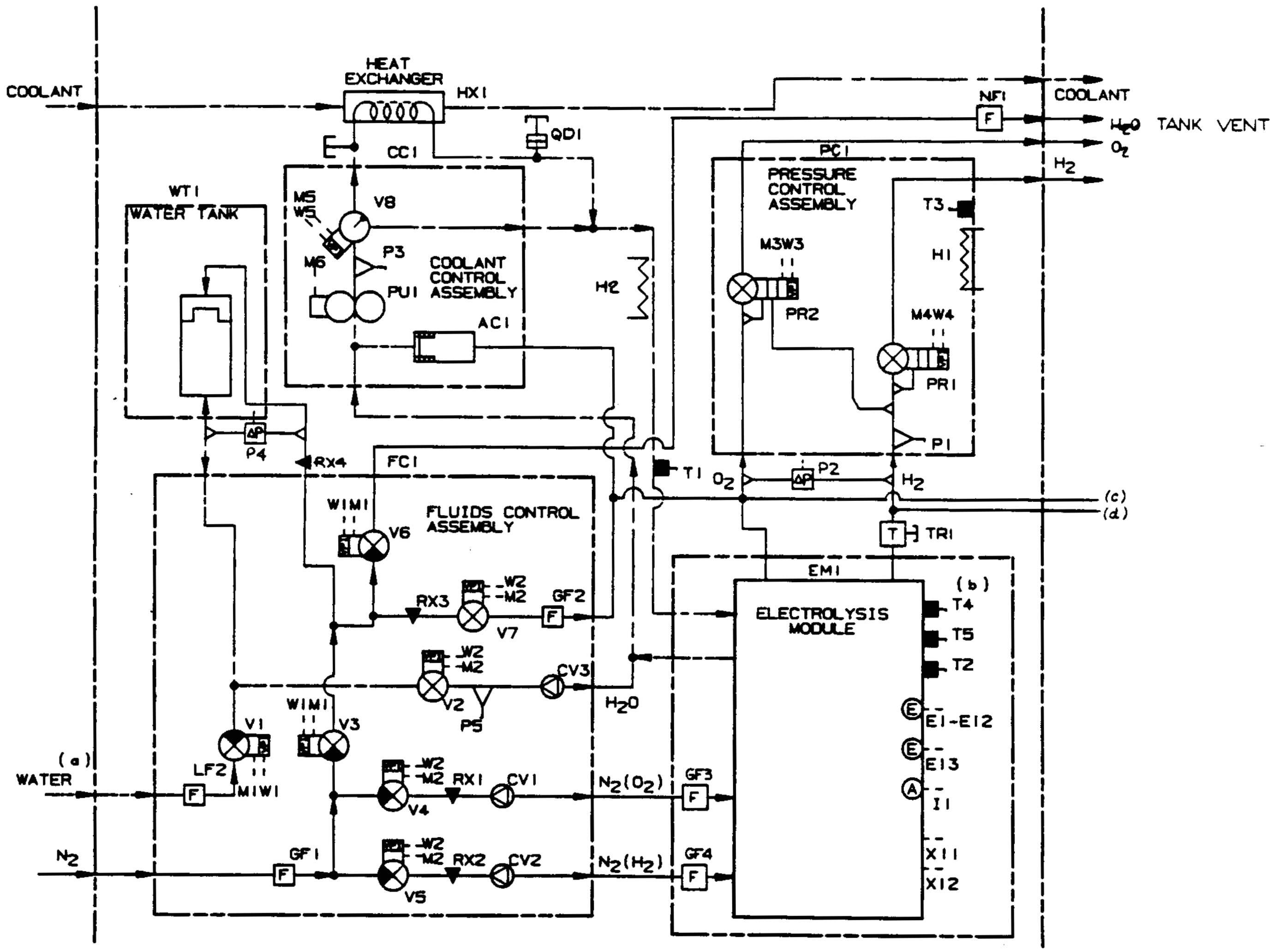
A comparison of the power needs of the systems described is shown in Table 3-10.

Table 3-10. Power Requirements and Heat Rejection Characteristics of Electrolysis Systems Gas Production Rate = 1.8 lb/h

Unit	Static Feed HSD	Anode Feed HSD	Static Feed LSI
Power Consumption (kW)	8.37	6.54	4.08
Heat Rejection (kW)	4.32	2.50	0.12

3.4.1 LSI Test Hardware Description

A schematic of LSI's SFE is provided in Figure 3-26, while Figure 3-27 is a photograph of the unit. The products O_2 and H_2 are generated in the static feed water electrolysis module (SFWEM). From the module, the product gases pass through the pressure control assembly (PCA) which monitors and adjusts SFE pressures to maintain proper differential pressures between the O_2, H_2, and water feed cavities of the SFWEM. A coolant control assembly (CCA) circulates water feed cavity fluid through the SFWEM for water feed and thermal control. The water is supplied to the SFWEM by a pressurized, cyclically filled water supply tank. The fill cycle of the water tank and the capability for N_2 purging of both the O_2 and H_2-containing cavities of the SFWEM are controlled by the fluids control assembly (FCA). A Control/Monitor Instrumentation (C/M I) Model 360 was used to provide automatic mode and mode transition control and self-protection.



(a) Potable Water from Water Management System.
(b) Included for Sensor Dedicated Shutdown Unit (SDSU).
(c) From TSA N_2 Purge/O_2 Side Backup.
(d) From TSA N_2 Purge/H_2 Side Backup.

Figure 3-26. Mechanical Schematic (SFE-3)

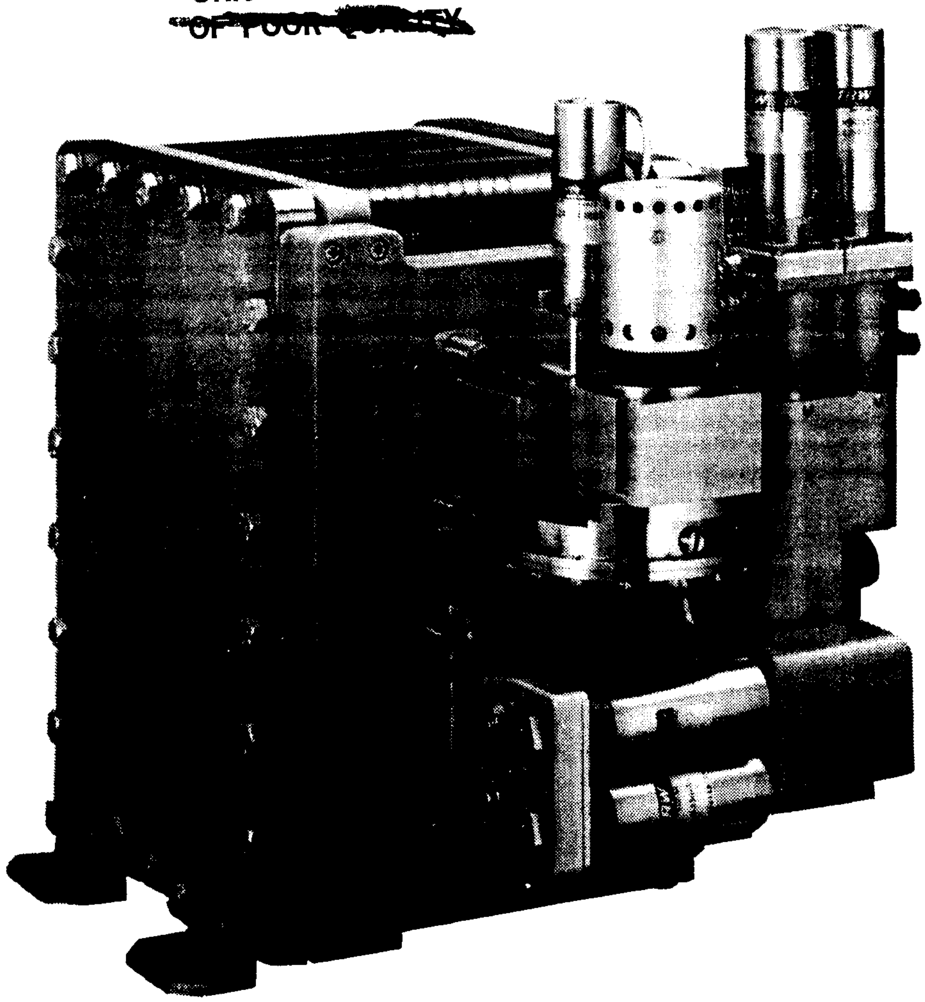


Figure 3-27. Life Systems Static Feed Electrolyzer

3.4.2 <u>HSD Test Hardware Description</u>

A schematic of the HSD SPE static water feed electrolysis subsystem is shown in Figure 3-28. Figure 3-29 is a photo of the five cell electrolysis unit.

The SPE oxygen/hydrogen generating subsystem electrolyzes water to produce oxygen and hydrogen gases at a maximum pressure of 1,000 and 960 psia, respectively. It consisted of a process package that included the SPE SFWEM, a dc power supply that provided the power necessary for electrolysis, a metal bellows accumulator with two 3-way valves to pressurize the feedwater, a driver box which provides electrical power and signal conditioning for various

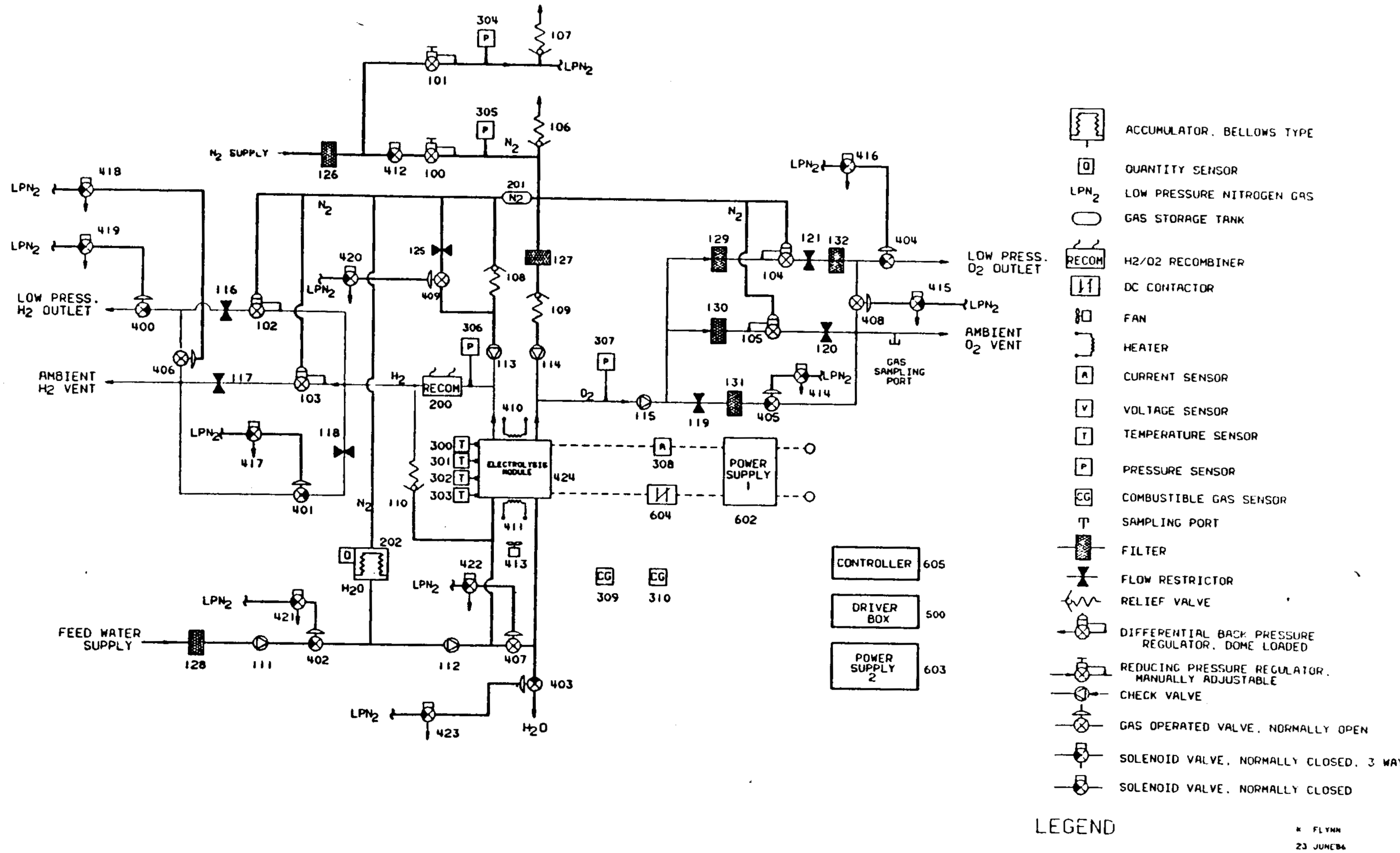


Figure 3-28. SPE Static Water Feed Electrolysis Subsystem (1,000 psia Operating Pressure)

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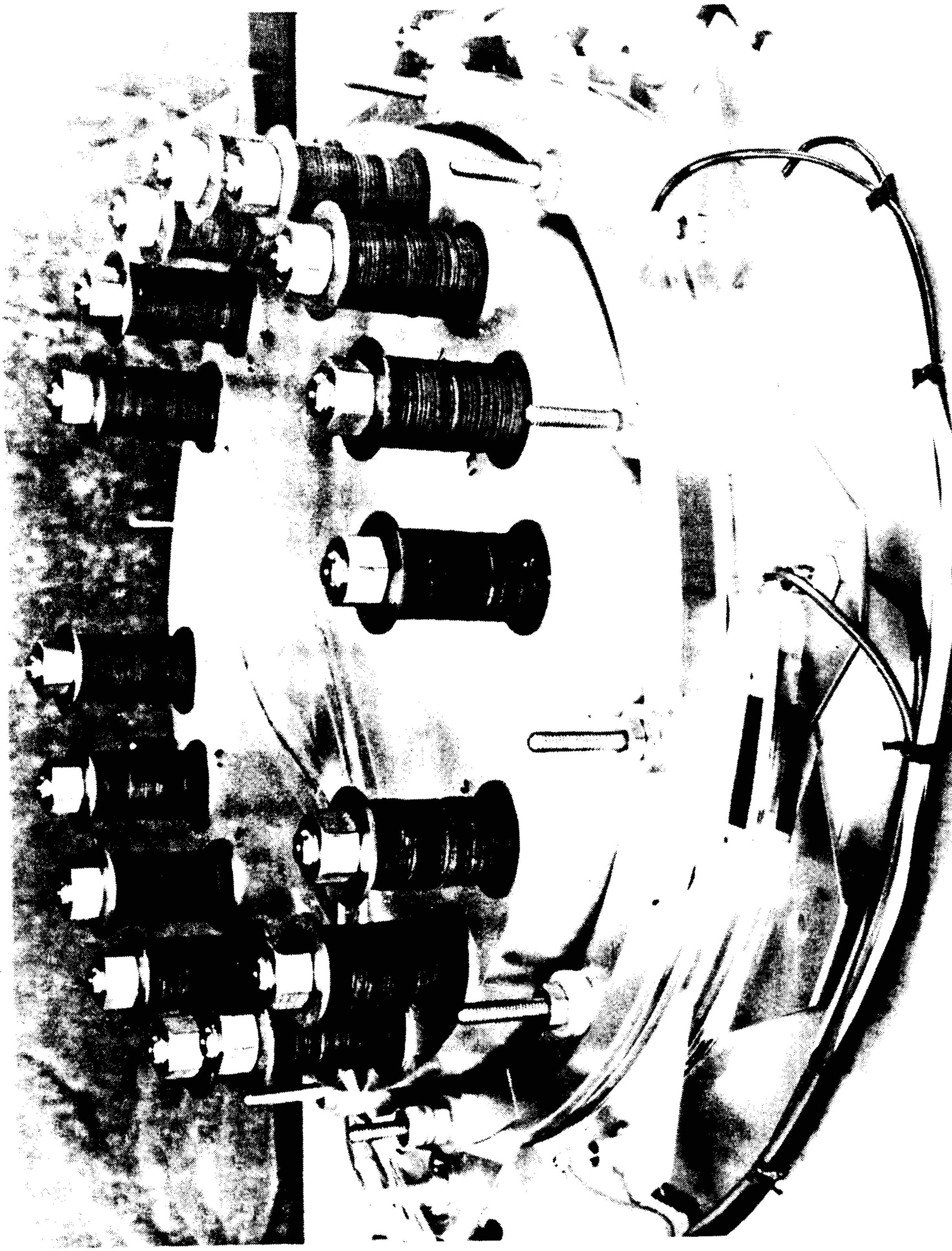

Figure 3-29. Hamilton Standard Five Cell Electrolysis Unit

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components in the process package and permitted mode monitor and control via the test bed Data General computer, and a controller which communicated with a Radio Shack TRS-80 Model 4D personal computer (see Figure 3-30). The process package, driver box, and controller were all mounted on an aluminum frame, while the metal bellows accumulator and valves were included as a separate package. The components were enclosed in a canister to isolate them from vacuum conditions.

The SPE subsystem interfaced with a Radio Shack TRS-80 personal computer as shown in Figure 3-30. The TRS-80 provided:

1. command signals to activate the SPE system,
2. caution and warning alarms enunciation and display, and
3. status monitoring.

The SPE driver box to Data General interface allowed the test bed Data General controller to have complete capability to monitor and control the SPE subsystem in the propulsion test facility. If the SPE subsystem or any one of the other subsystems change their operating status, the Data General could configure the other subsystems to the proper corresponding mode for proper operation or safety.

3.5 THRUST MEASURING SYSTEM DESIGN SUMMARY

A thrust measuring system (Figure 3-31) for use on the test bed was added to the contract. This was designed and fabricated at Rocketdyne for either horizontal or vertical use and was to be calibrated remotely at vacuum conditions with thruster propellant lines pressurized to remove all external load effects.

The thrust system was delivered to MSFC and on the test bed installed in February 1987. The first thruster firings to obtain data from it were performed in March. Figure 3-32 shows the thruster mounted with thrust system on the test bed. Appendix A includes the detail drawings of the thrust measuring system.

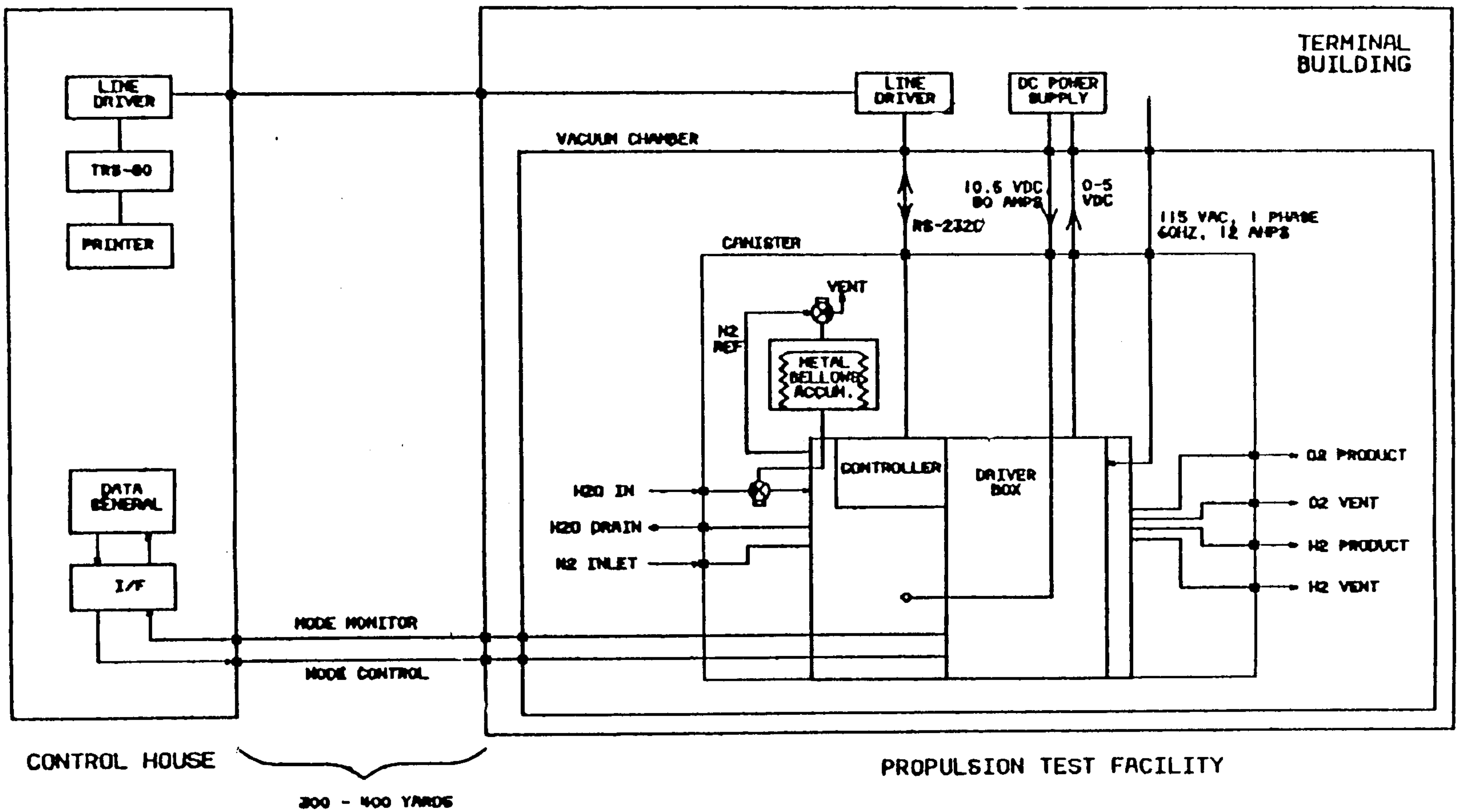

Figure 3-30. Facility Interface Block Diagram

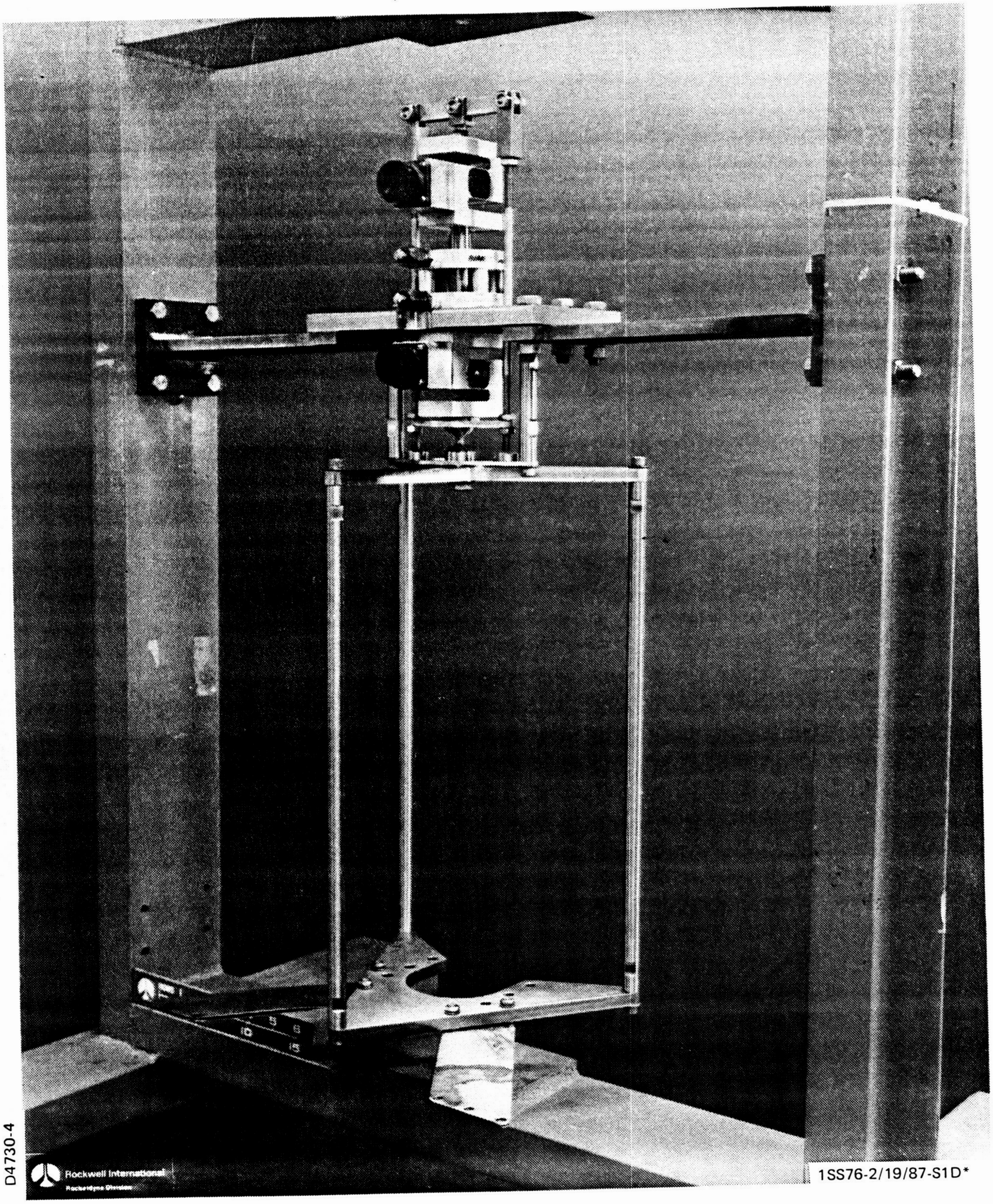

Figure 3-31. Thrust Measuring System Before Installation in Test Bed

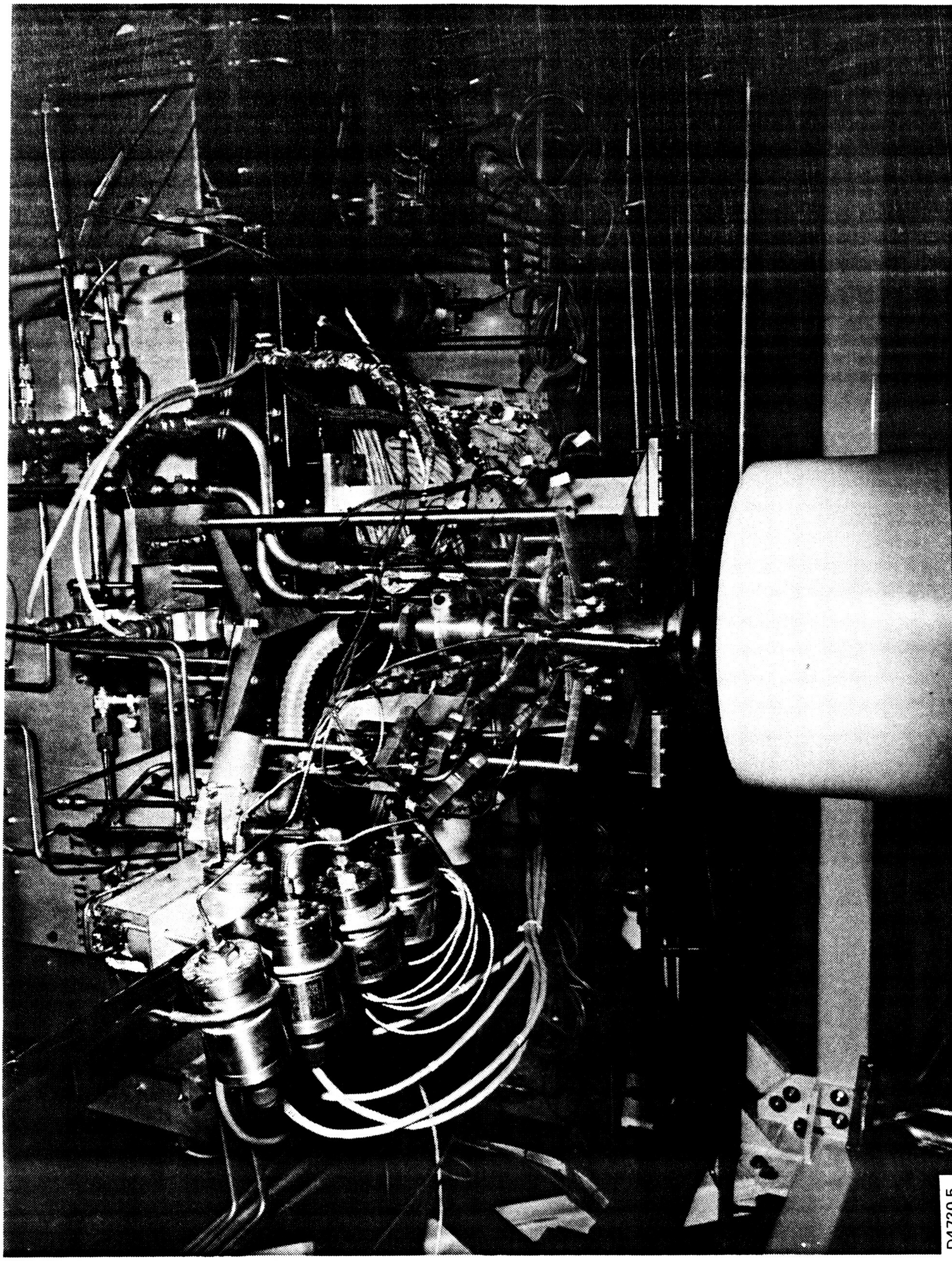

Figure 3-32. Rocketdyne Prototype Thruster in Thrust Measuring System for Checkout of System on Test Bed

Initial test data results indicated a discrepancy of about 3 lb between the calculated and measured values. A series of calibration checks were made which revealed that the mount on the stand was flexing, thereby allowing the entire thrust system to move. The movement introduced additional load paths through the propellant plumbing which reduced the load cell readings. Additional braces were added to the test bed mounting, and the movement was reduced to acceptably low levels. The thrust calibration and measuring systems were shown to be working within 0.1% and the data was expected to be within 1% including any residual movement.

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4.0 25-lbf THRUSTER MODIFICATIONS AND TESTING

In early 1986 the availability of thrusters for use with the test bed at the high mixture ratio (8:1) needed for water electrolysis became a critical issue. To demonstrate the feasibility of operation at this level, funding was added to modify a thruster that Rocketdyne had supplied to NASA-MSFC for testing at mixture ratio 4:1. A redesigned injector was fabricated and the existing thrust chamber (Figure 4-1), which had already been fired for over 12 h, was modified. Figure 4-2 shows the overall arrangement of the redesign (prototype) and indicates the instrumentation locations.

The prototype thruster was supplied to MSFC in April 1986 and a test series was carried out in test stand A-300 by MSFC personnel with Rocketdyne support present. A summary of the testing is presented in Tables 4-1 and 4-2. The prototype thruster assembly was fired at a nominal chamber pressure of 100 psia, a propellant mixture ratio of 8:1 and at vacuum conditions. A total of 11.1 h firing time was accumulated in 11 tests with one 6.1 h continuous run performed. The posttest hardware condition was excellent.

The test results section displays prototype thruster test bed testing results and Reference 1 has a complete discussion of all 25 lbf thruster operations.

To illustrate the capability of the prototype thruster to work with the test bed or flight system, a mixture ratio excursion was conducted (Figure 4-3). Pressure response during this test is shown in Figure 4-4 and thermal performance in Figure 4-5.

Based on the results of these tests, the prototype thruster, with slight additional preparation, was ready for integration into the test bed and testing with the electrolysis system which operated at a mixture ratio of 8:1.

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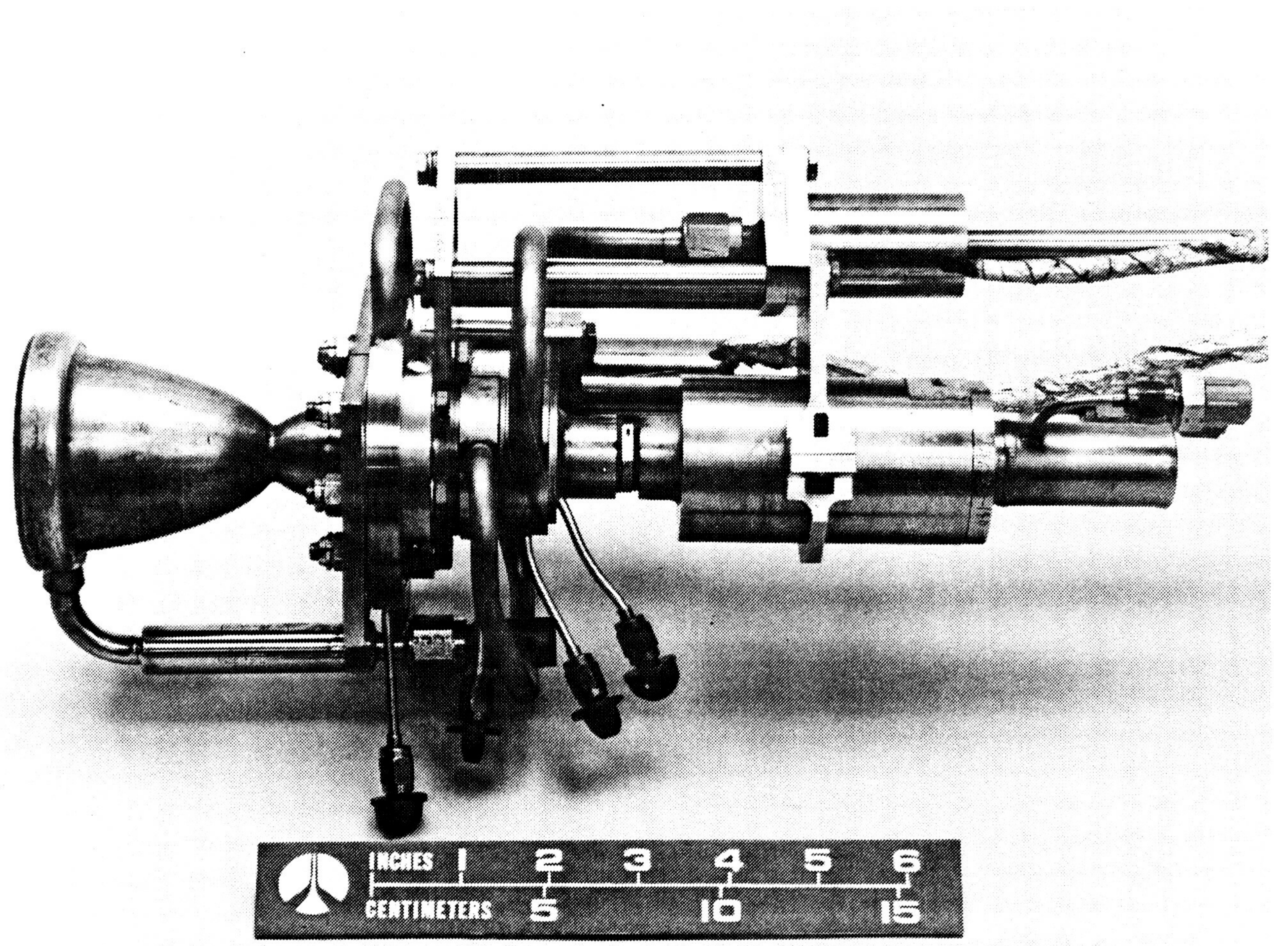

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Figure 4-1. Rocketdyne Prototype 8:1 Thruster

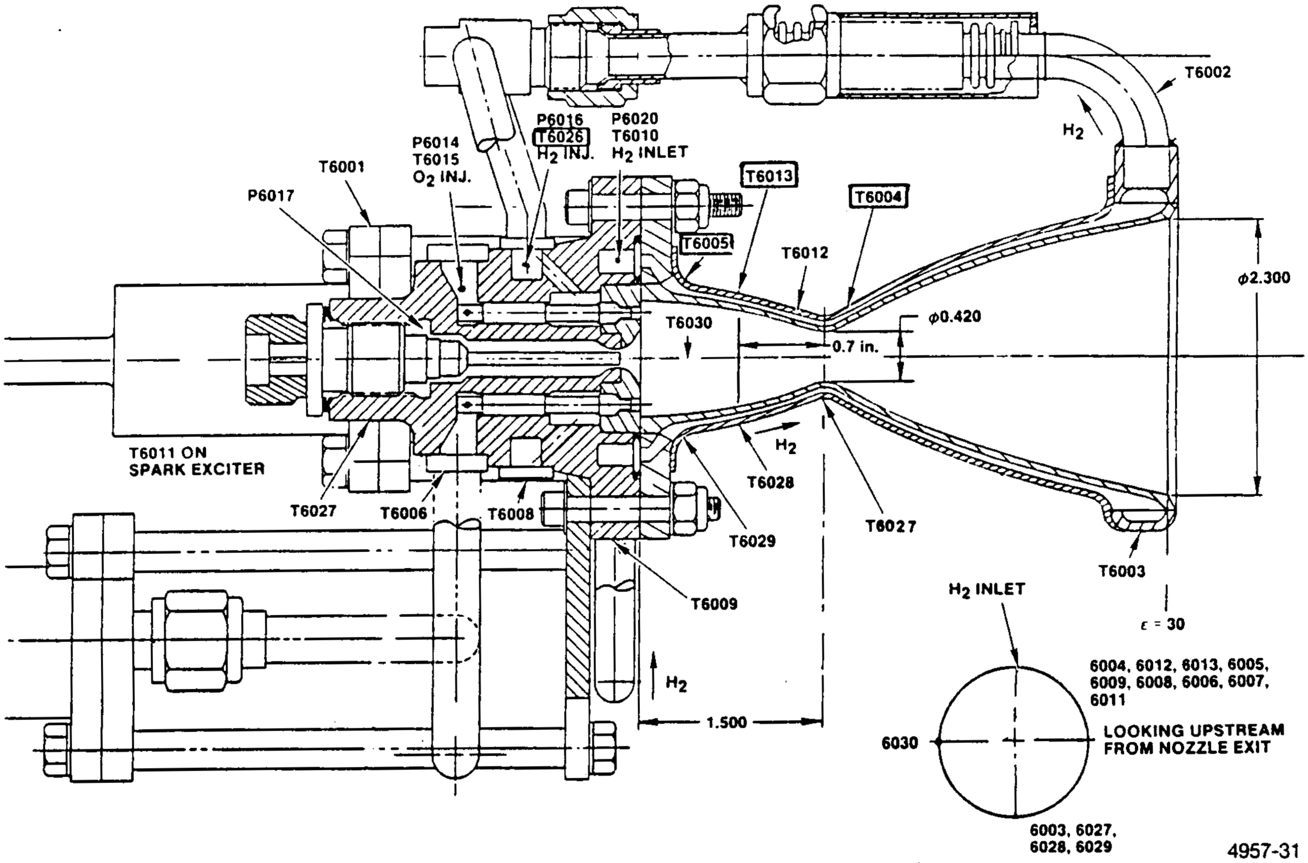

Figure 4-2. Prototype 25-lbf GO_2/GH_2 Thruster

Table 4-1. Prototype 25-lbf GO_2/GH_2 Thruster Test Summary (MR = 8)

TEST FACILITY	NASA MSFC TEST STAND 300 VACUUM TEST CELL
THRUSTER CONFIGURATION	COAXIAL INJECTOR WITH COPPER FACE, DOWN-PASS COOLING OF THRUST CHAMBER, 40% BLC
ACCUMULATED RUN DURATION (h)	11.5
TOTAL IMPUSE AT MR = 8 (lb-s)	1.0 MILLION
MAXIMUM RUN DURATION AT MR = 8 (h)	6.1
TOTAL RUN DURATION AT MR = 8 (h)	11.1
MIXTURE RATIO RANGE	TRAVERSED FROM 7.9 TO 5.1 DURING 1500 s TEST
C* EFFICIENCY AT MR = 8 (%)	91
ESTIMATED VACUUM I_{sp} AT MR = 8 (ϵ = 30) (s)	360
THRUST (CALC) AT MR = 8 (ϵ = 30) (lbf)	27
CONDITION OF HARDWARE FOLLOWING TESTS	EXCELLENT

86D-9-732

Table 4-2. High Mixture Ratio Test Summary

TEST NUMBER	TEST DATE	MIXTURE RATIO	TEST DURATION (s)
P102-155	4-21-86	8	2
156		8	10
157		8	22
158	4-22-86	7.8	10
159		8.1	30
161		7.9	60
162		8.1	600
163		8.0	12,640
164	4-23-86	7.9-5.1	1,500
165		8.2	4,500
166		8.0	22,000
		TOTAL	41,374

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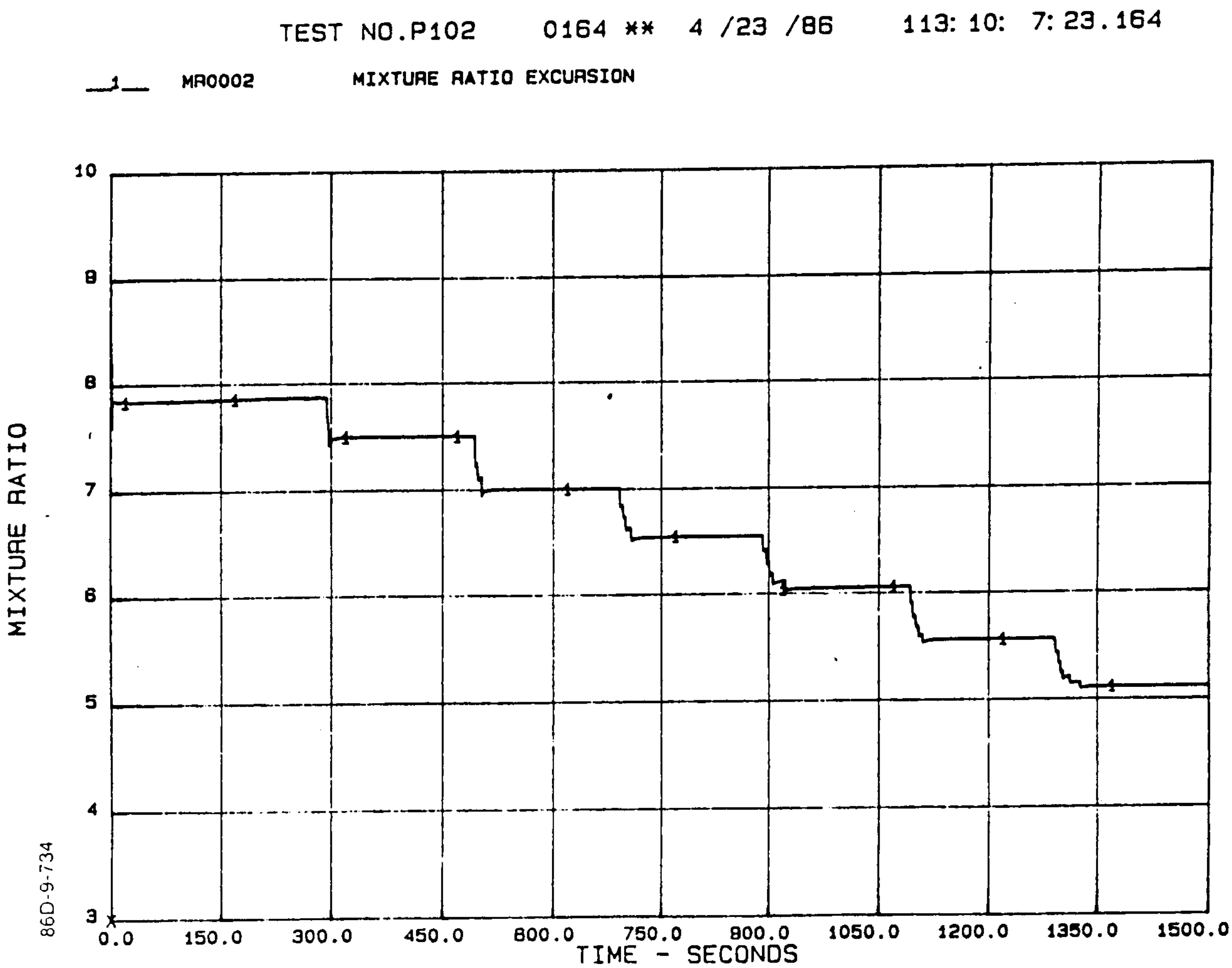

Figure 4-3. Mixture Ratio Excursion

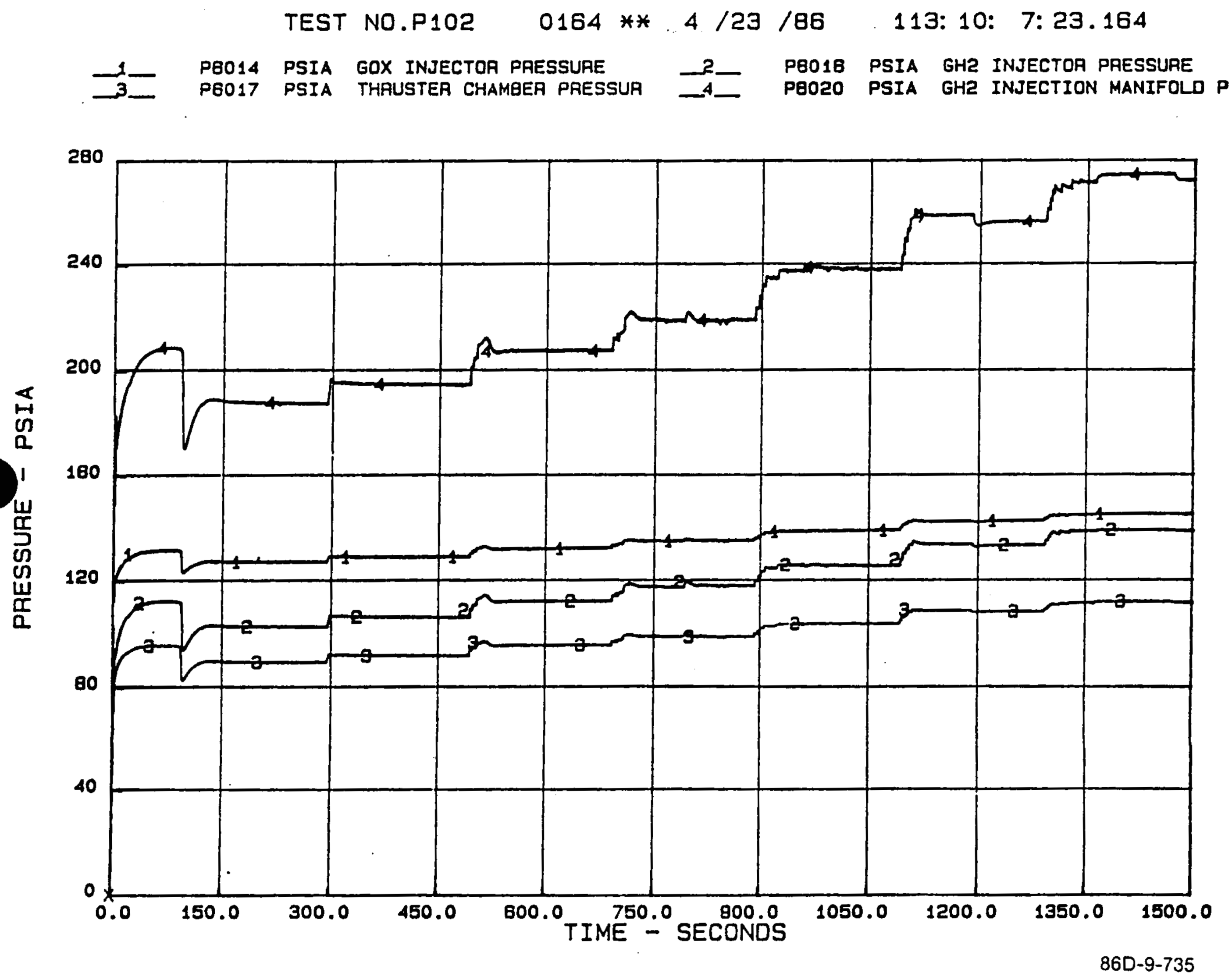

Figure 4-4. Thruster Pressure Response

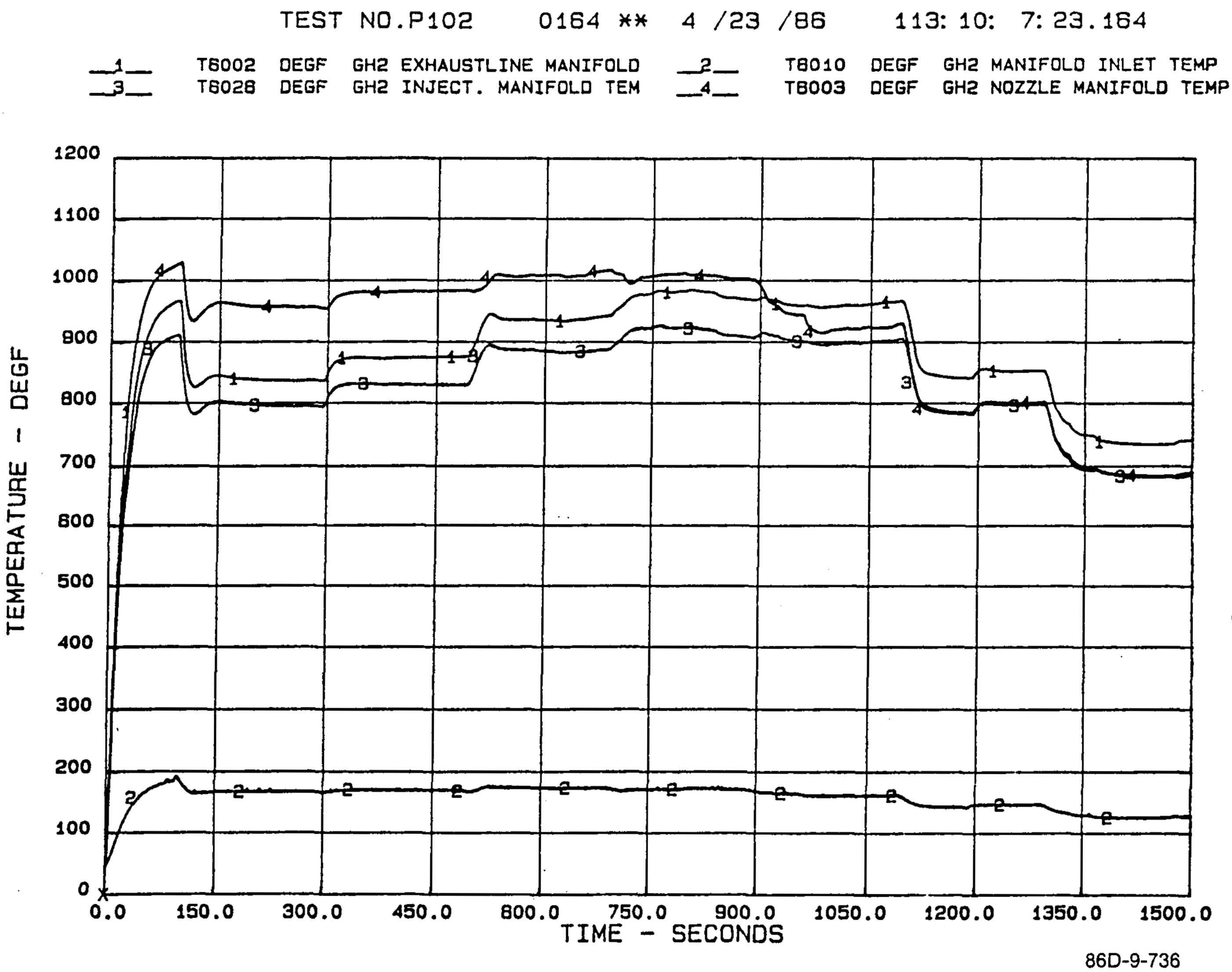

Figure 4-5. Thruster Thermal Performance (Sheet 1 of 4)

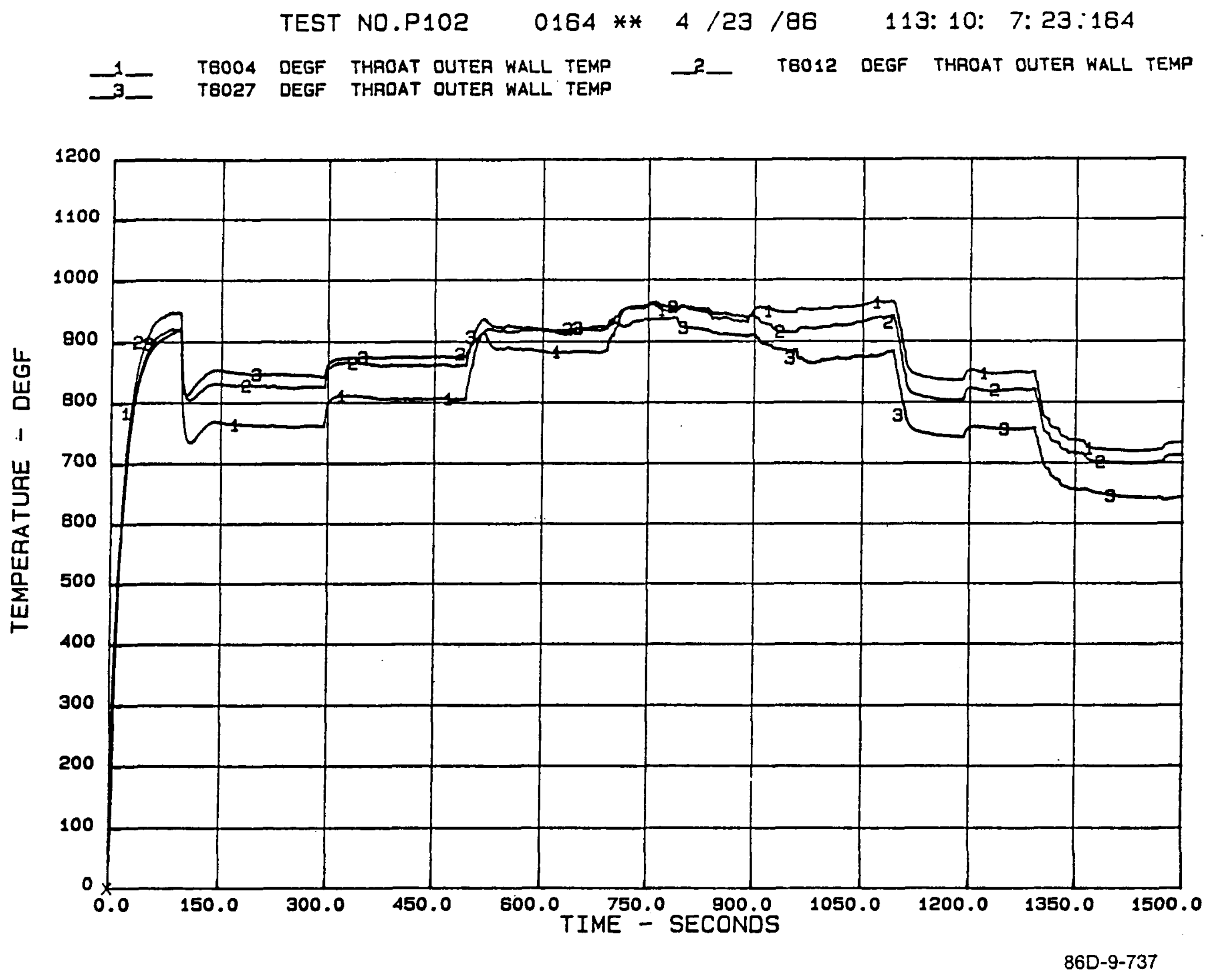

Figure 4-5. Thruster Thermal Performance (Sheet 2 of 4)

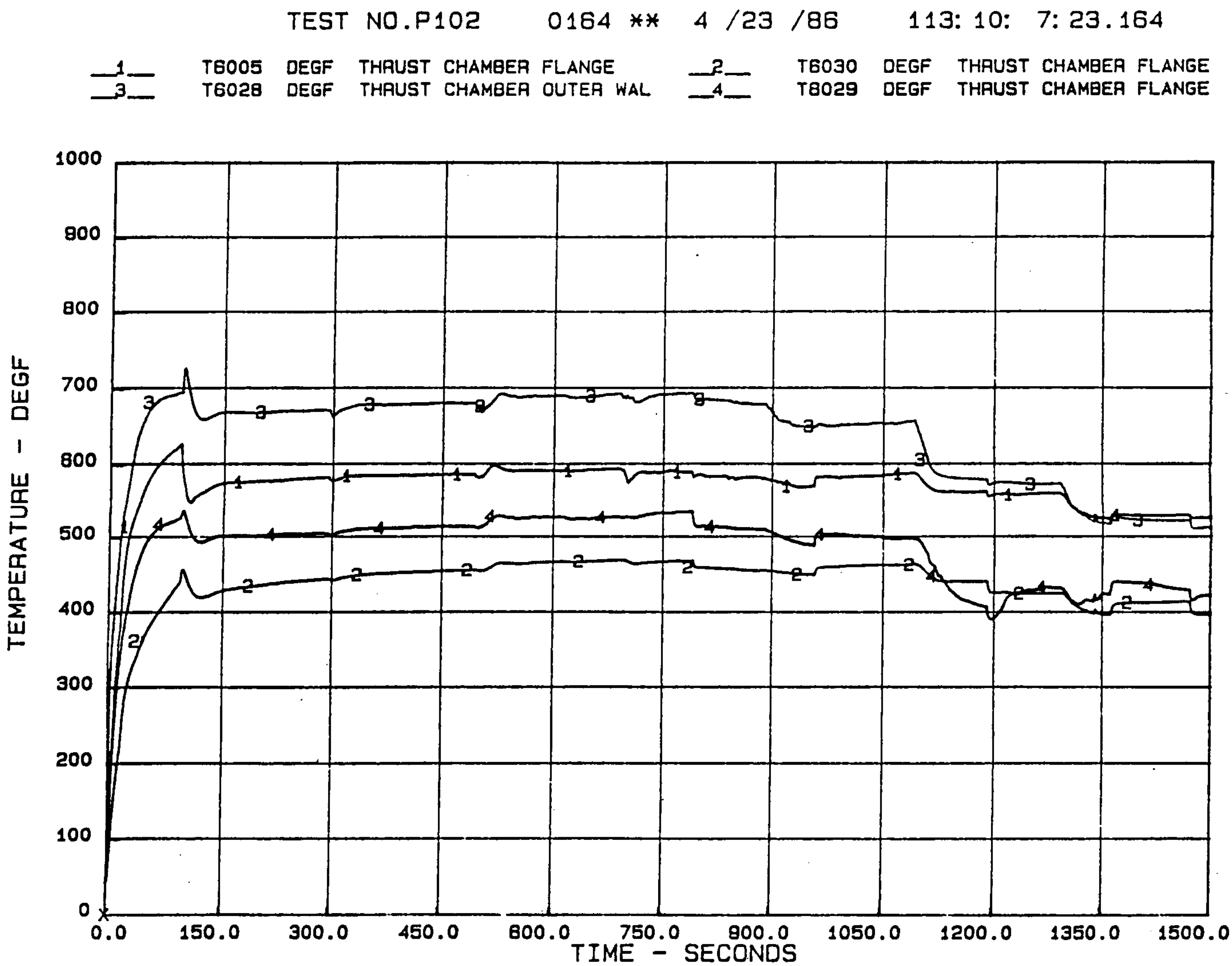

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Figure 4-5. Thruster Thermal Performance (Sheet 3 of 4)

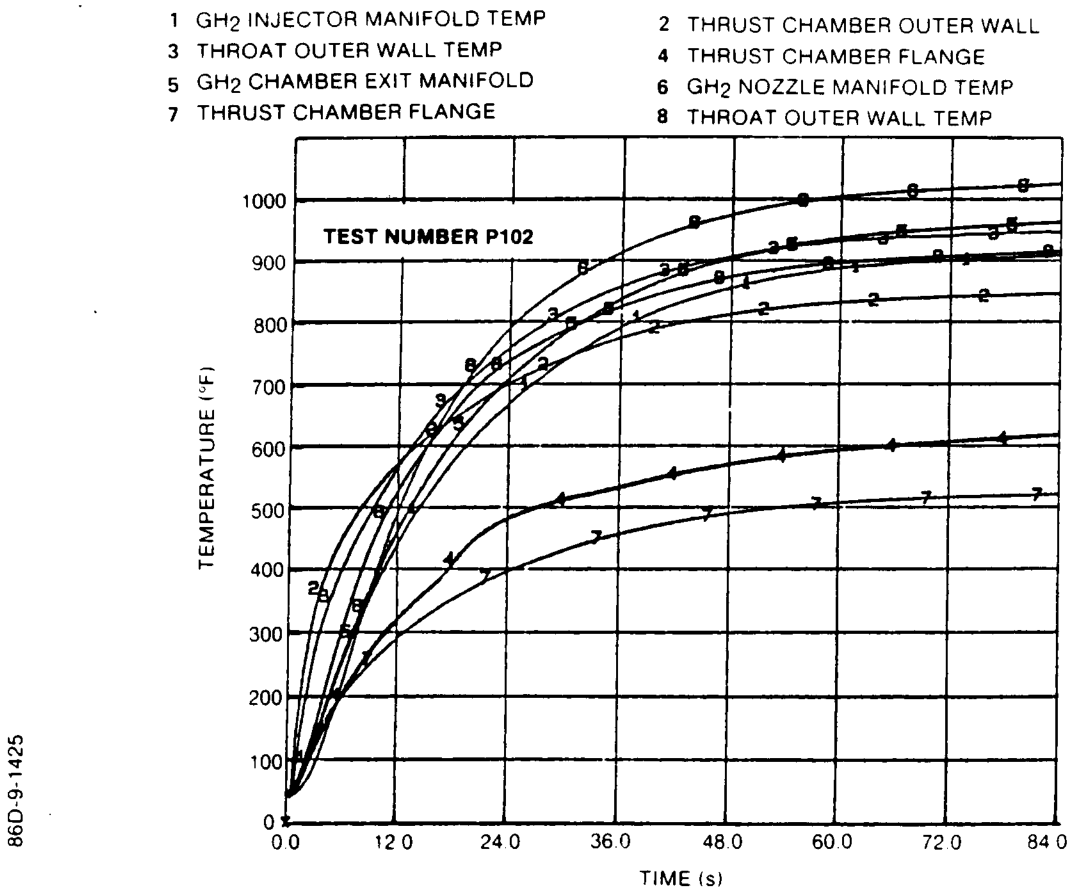

Figure 4-5. Thruster Thermal Performance (Sheet 4 of 4)

5.0 TEST RESULTS

Acceptance tests of the propulsion module were conducted in October and early November 1986 (tests 001 through 003). The sequence was designed to simulate thruster and resistojet firing by bleeding the gas through dump valves. Since the original design was for a 4:1 mixture ratio thruster, the acceptance tests were performed at those conditions.

Following the acceptance tests the Rocketdyne 25-lbf prototype thruster was installed in the test bed. A series of tests (tests 004 through 024) were performed starting in December 1986 culminating with a 291 s thruster firing.

The electrolysis system testing (tests 025 through 028) began in early July 1987 with a complete LSI 350-psig electrolysis system checkout test including operation of the dryers. The LSI 350-psig electrolysis test was begun in late July. The test proceeded for three days until system pressures dropped sharply, indicating leakage in the gaseous hydrogen system. Subsequent checks revealed KOH in the lines upstream of the dryer because of a malfunction in the electrolysis unit, apparently caused by pressures erroneously applied to purge points. The KOH had attacked components in the system plumbing, causing leakage. The test was considered a qualified success in that gas was produced and delivered to the storage tanks at up to 160 psig under automatic control prior to the malfunction.

The HSD 1,000-psi unit was installed in late October 1987. The test series (tests 075 through 092) was started on October 22 and completed successful operation on December 1 with a 175 s firing of the 25-lbf thruster using the gases generated at 1,000 psia by the electrolysis unit.

Prior to and following completion of the HSD electrolysis tests, tests 029 through 074 and tests 093 through 188 were conducted on flight-type thrusters designed for NASA-LeRC contract NAS3-25142 representing an updated version of the prototype thruster. These thrusters were fabricated by Rocketdyne for NASA-LeRC and are described in Reference 1. Up to 14 tests per day were

performed simulating multiple firings of the system. Experimental low-heat-flux injectors and advanced ignition systems for the 25-lbf thruster were also evaluated.

A summary of all tests performed on the test bed is presented in Appendix B. A detailed discussion of thruster test results is included in Reference 1.

Following completion of the thruster tests, the test bed was removed from the vacuum chamber and stored.

With the activation and operation of the WEUs on the test bed, the first simulation of the space station baseline propulsion system provides assurance and data for the flight design, and demonstrates the technical readiness of this cost-effective, safe, high-performance system. All major hardware components and control systems were represented, producing data directly applicable to the future design and development of the flight propulsion system. Successful operation of the end-to-end propulsion system was demonstrated.

5.1 PROPULSION MODULE TESTING

Prior to actual testing several checkout operations were performed. The control system was tested in several ways to verify satisfactory operation. The system software and hardware were verified by running a checkout test program which cycled all the system software commands and input/output channels. The transducer channels were all verified by comparing the resultant data to that from similarly located channels on the test facility data acquisition system.

A series of preacceptance, acceptance, and system evaluation tests were conducted on the space station propulsion test bed. Redundant instrumentation systems were provided for the data recording function and the control function.

The initial acceptance test (P103-2) was conducted using gaseous nitrogen (GN_2) to simulate oxygen and gaseous helium (GHe) to simulate hydrogen. The test was conducted using the sequence of Table 5-1. The sequence description

Table 5-1. Initial Acceptance Test Sequence

Time (Relative) (s)	Event	Valve Identification (Figure 3-10)
0.25	Hydrogen and oxygen accumulator outlet valves open	31
1.20	Initiate hydrogen line pressurization	33
15.80	Hydrogen line pressurization complete	33
15.88	Initiate oxygen line pressurization	33
29.18	Oxygen line pressurization complete	33
29.26	Initiate resistojet line pressurization	42
48.82	Resistojet line pressurization complete	42
71.16	Initiate resistojet	C
121.18	Complete resistojet firing	C
126.16	Initiate thruster firing	A&B
688.02	Complete thruster firing	A&B
688.02	Initiate test bed safing	-
728.00	Facility test bed safing	-

was initiated after the hydrogen and oxygen accumulators were charged from a facility supply. Representative typical data from this test are given in Figures 5-1 and 5-2. Figure 5-1 shows the accumulator pressure and temperature and the venturi and thruster inlet pressures for the oxidizer system. The same data are given in Figure 5-2 for the hydrogen system. The test was terminated when the oxidizer tank pressure decayed to 300 psia. A comparison between the measured and calculated tank pressures are given in Figure 5-3. The calculated values were based on an 80% isothermal condition.

GO_2 and GH_2 were used as the test fluids on the final acceptance test. These data are presented in Figures 5-4 through 5-9. Figure 5-4 shows the GO_2 accumulator pressure. Figure 5-5 gives the same pressure data for the GH_2 system. Temperature data are given in Figures 5-6 and 5-7 for the oxidizer system and in Figures 5-8 and 5-9 for the hydrogen system. The oxidizer system characteristics were the same for both the nitrogen and oxygen use

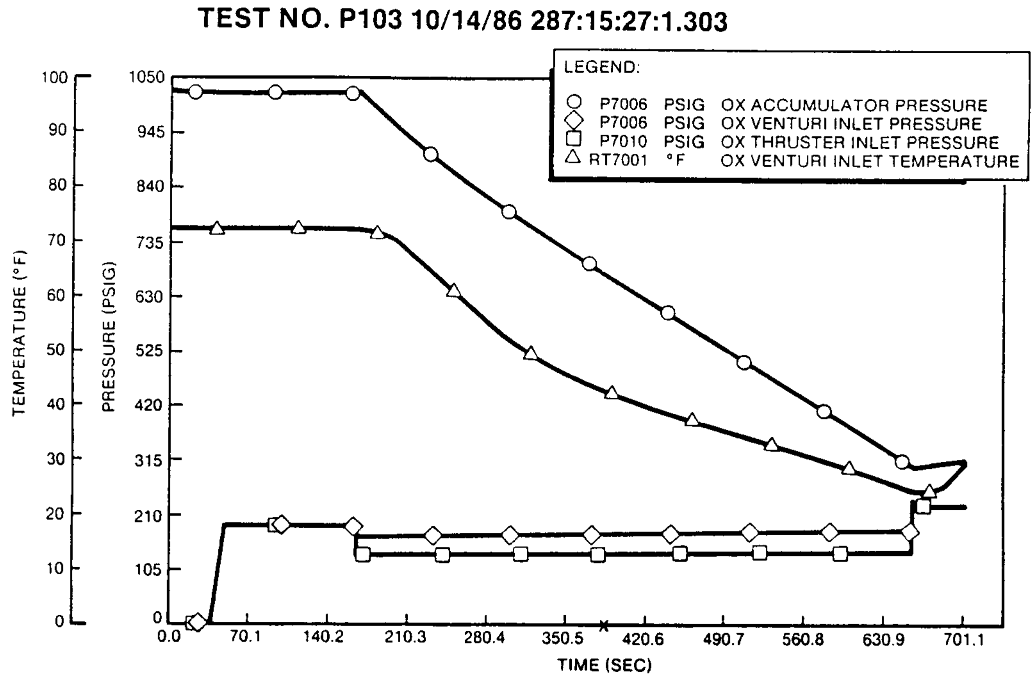

Figure 5-1. Oxidizer System Blowdown Data (GN_2 Used in Place of GOX)

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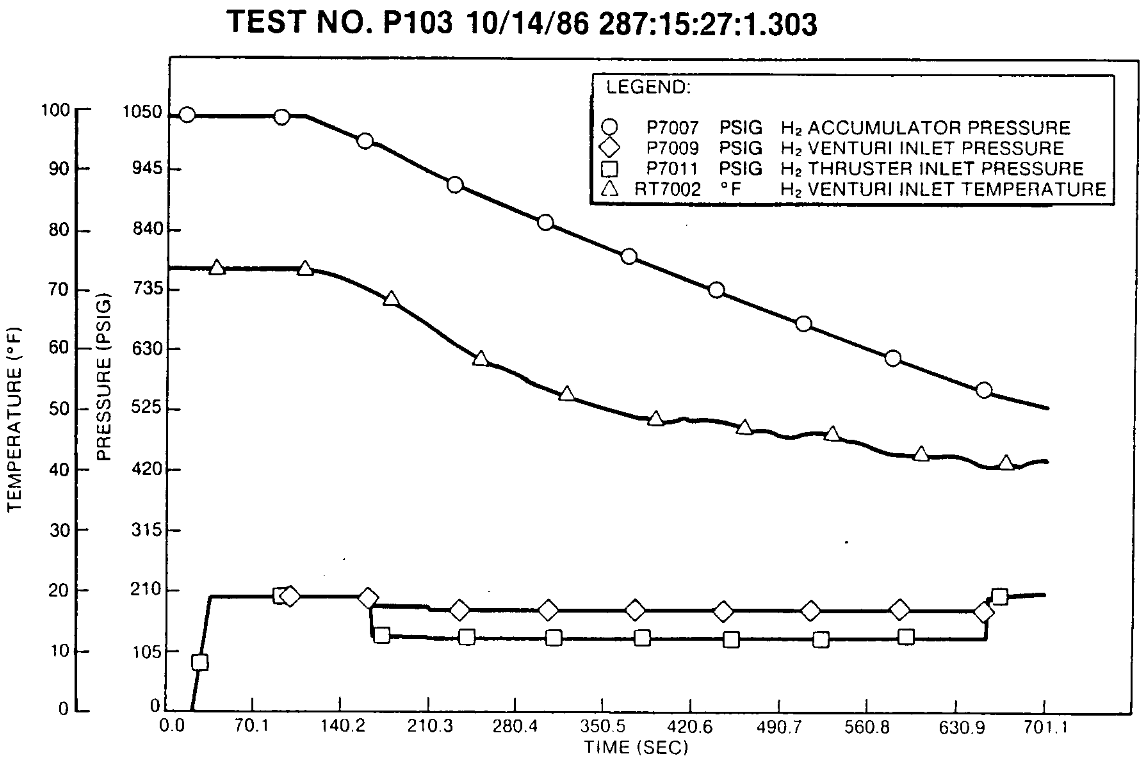

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Figure 5-2. Fuel System Blowdown Data (GHe Used in Place of GH_2)

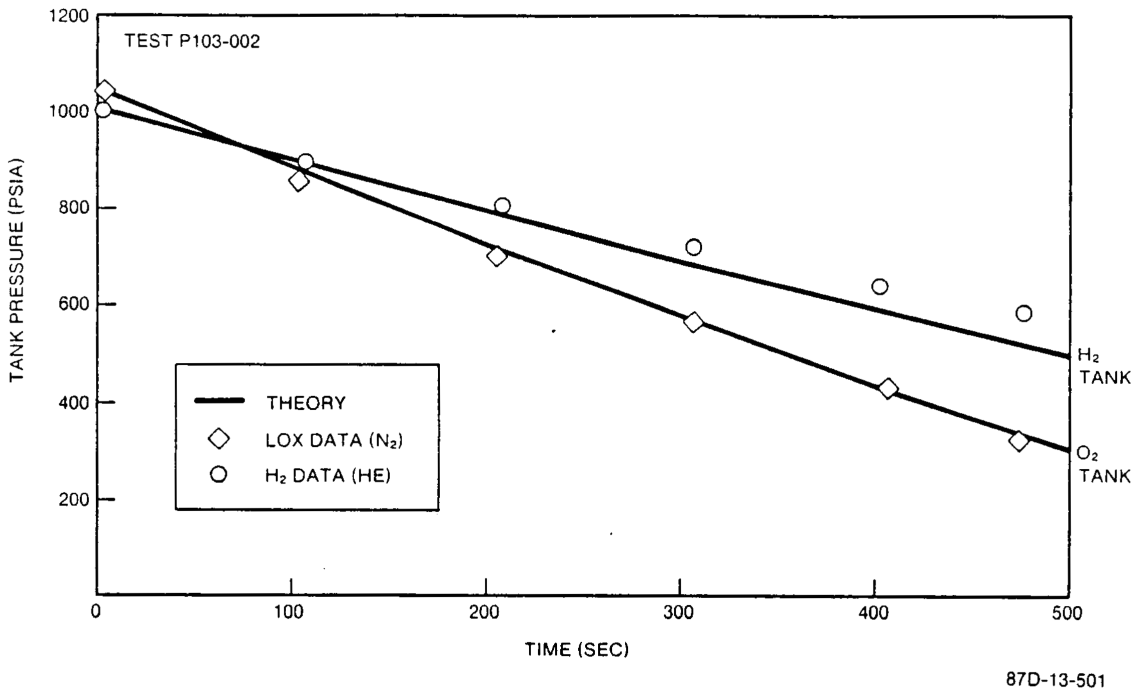

Figure 5-3. Comparison of Tank Pressures from Blowdown Versus Theoretical 80% Isothermal

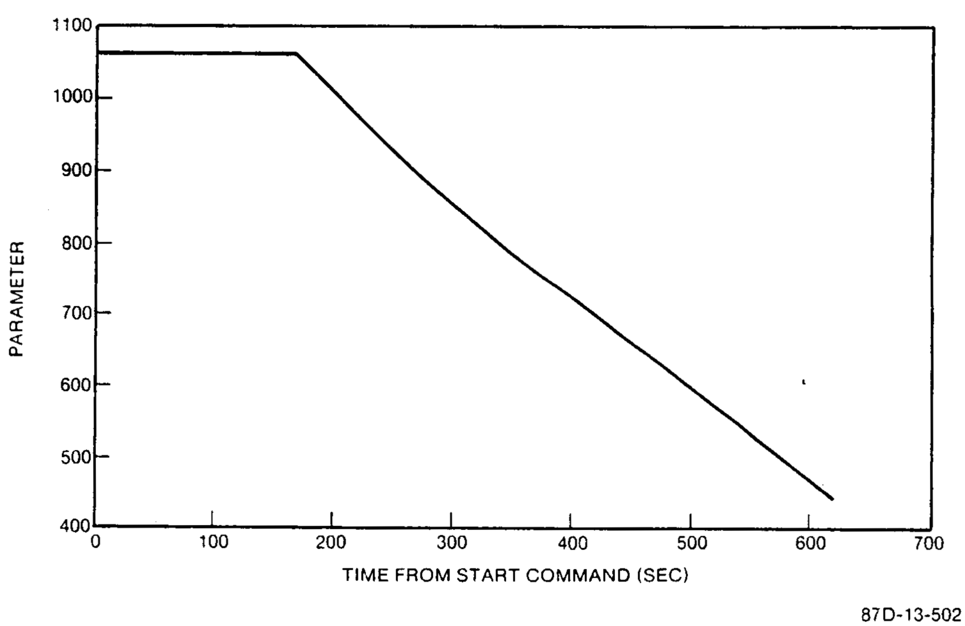

Figure 5-4. Oxidizer Accumulator Pressure During Acceptance Test

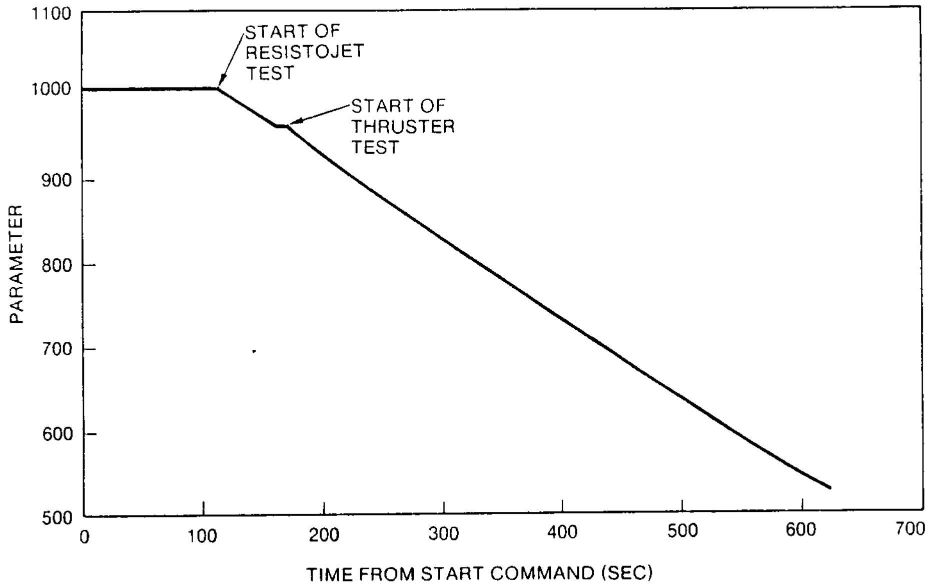

Figure 5-5. Fuel Accumulator Pressure During Acceptance Test

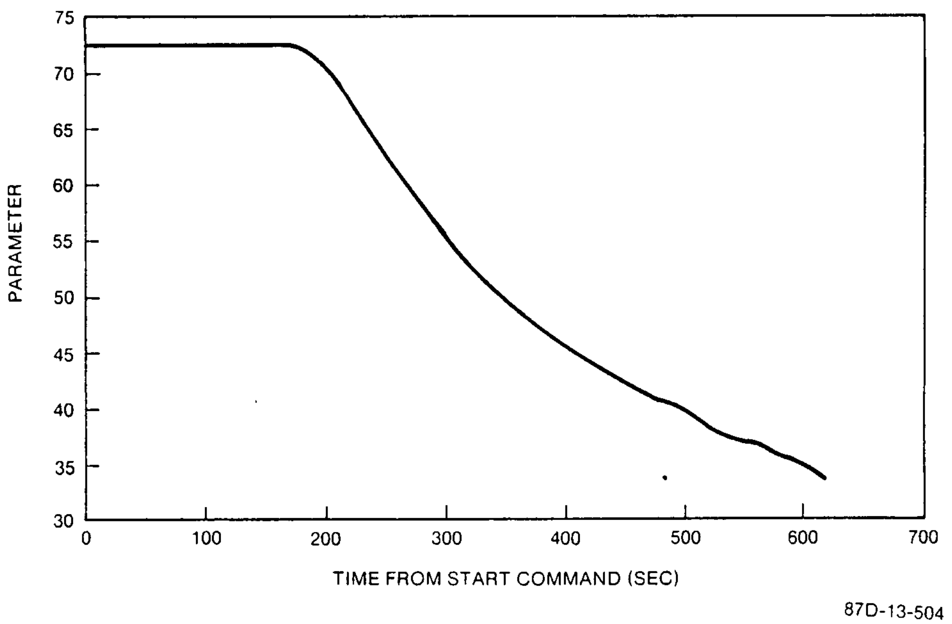

Figure 5-6. Oxidizer Accumulator Outlet Temperature During Acceptance Test

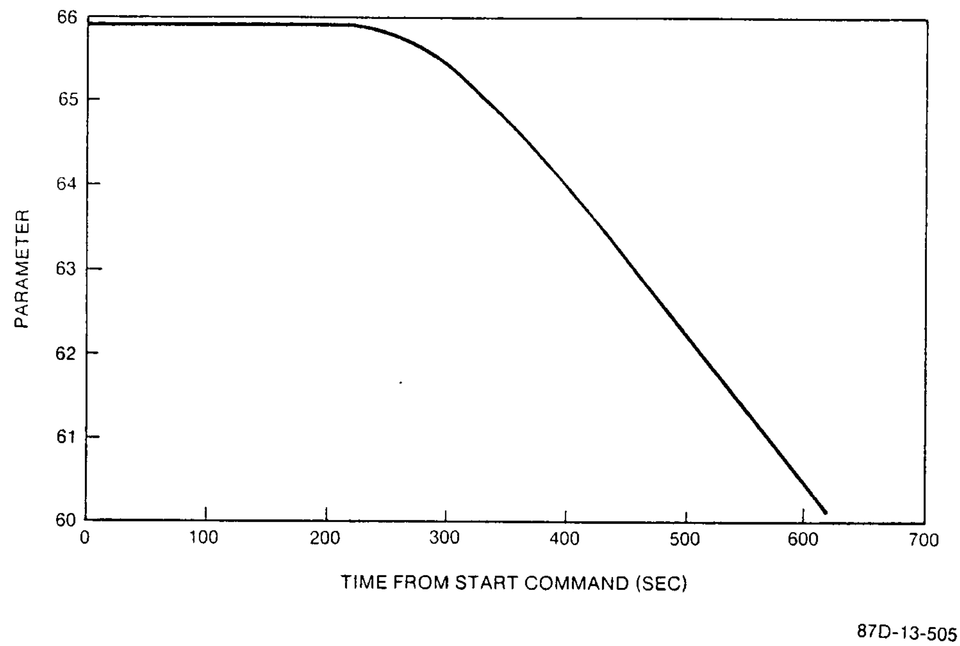

Figure 5-7. Oxidizer Accumulator Skin Temperature During Acceptance Test

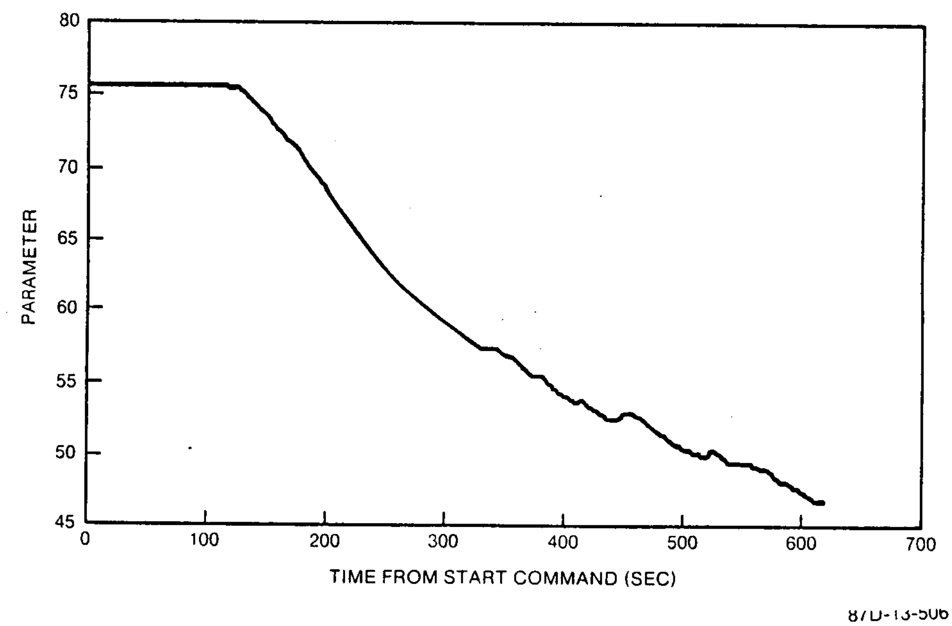

Figure 5-8. Fuel Accumulator Outlet Temperature During Acceptance Test

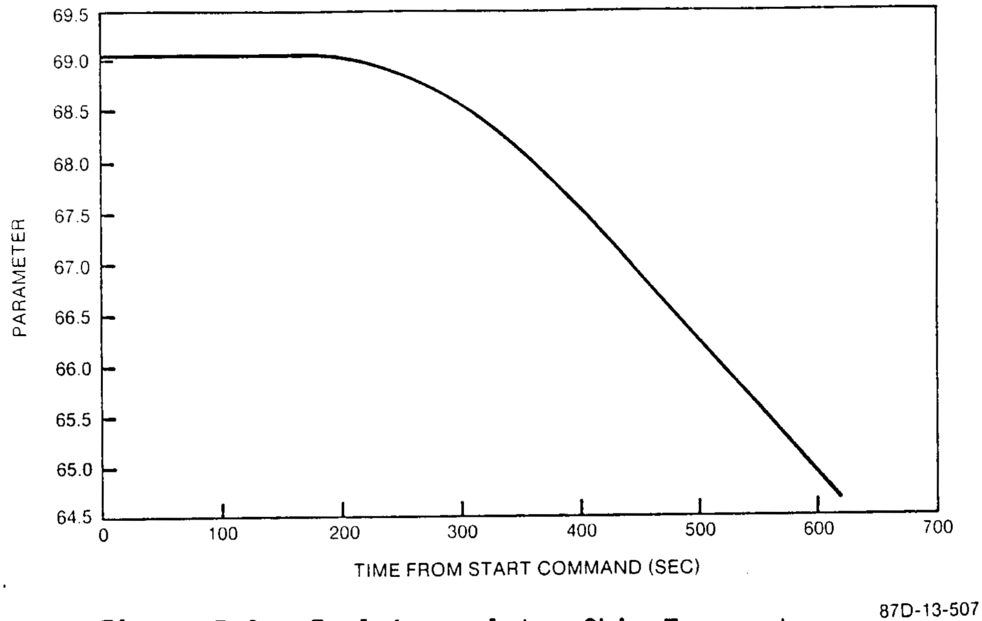

Figure 5-9. Fuel Accumulator Skin Temperature During Acceptance Test

fluids, as expected. However, the hydrogen and helium tests exhibit different thermal characteristics. This was also expected and the observed thermal and hydraulic differences were predictable.

Following the acceptance tests, the Rocketdyne 25-lbf prototype thruster (Figure 5-10) was installed in the test bed. To turn the exhaust gas away from the cell floor, a facility water-cooled exhaust duct was placed beneath the engine shown in Figure 5-11. Minor modifications were made to the test bed plumbing to run the thruster at the new design point of 8:1 mixture ratio. A series of tests were conducted on the system in December 1986, culminating with the thruster firing for 291 s, the oxygen tank maximum duration at these conditions.

To demonstrate the totally automated capability of the system, one of the firings during the thruster series was performed from California. After setup was completed, control of the system was switched to the Rocketdyne remote terminal and a 5 s thruster firing was satisfactorily conducted from a 2,000-mi distance.

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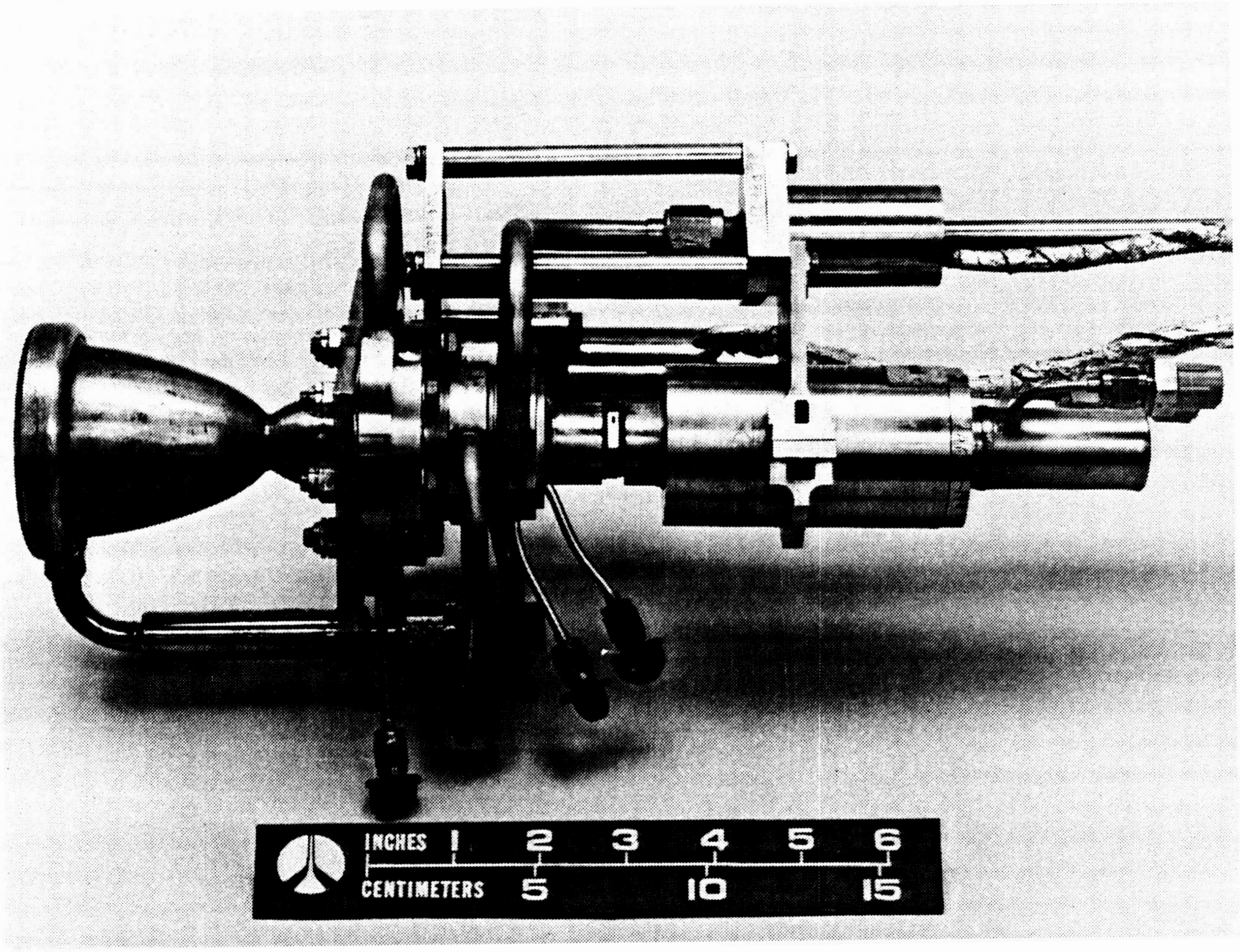

D4730-2

Figure 5-10. Rocketdyne Prototype 8:1 Thruster

5.2 THRUSTER PERFORMANCE RESULTS

The prototype thruster data summarized in the thruster modifications portion (Section 4.0) of this report were used as a baseline for combustion performance (C*) to predict the performance of the LeRC thruster. The JANNAF performance prediction codes and a Rocketdyne boundary layer loss model were used to complete the performance modeling.

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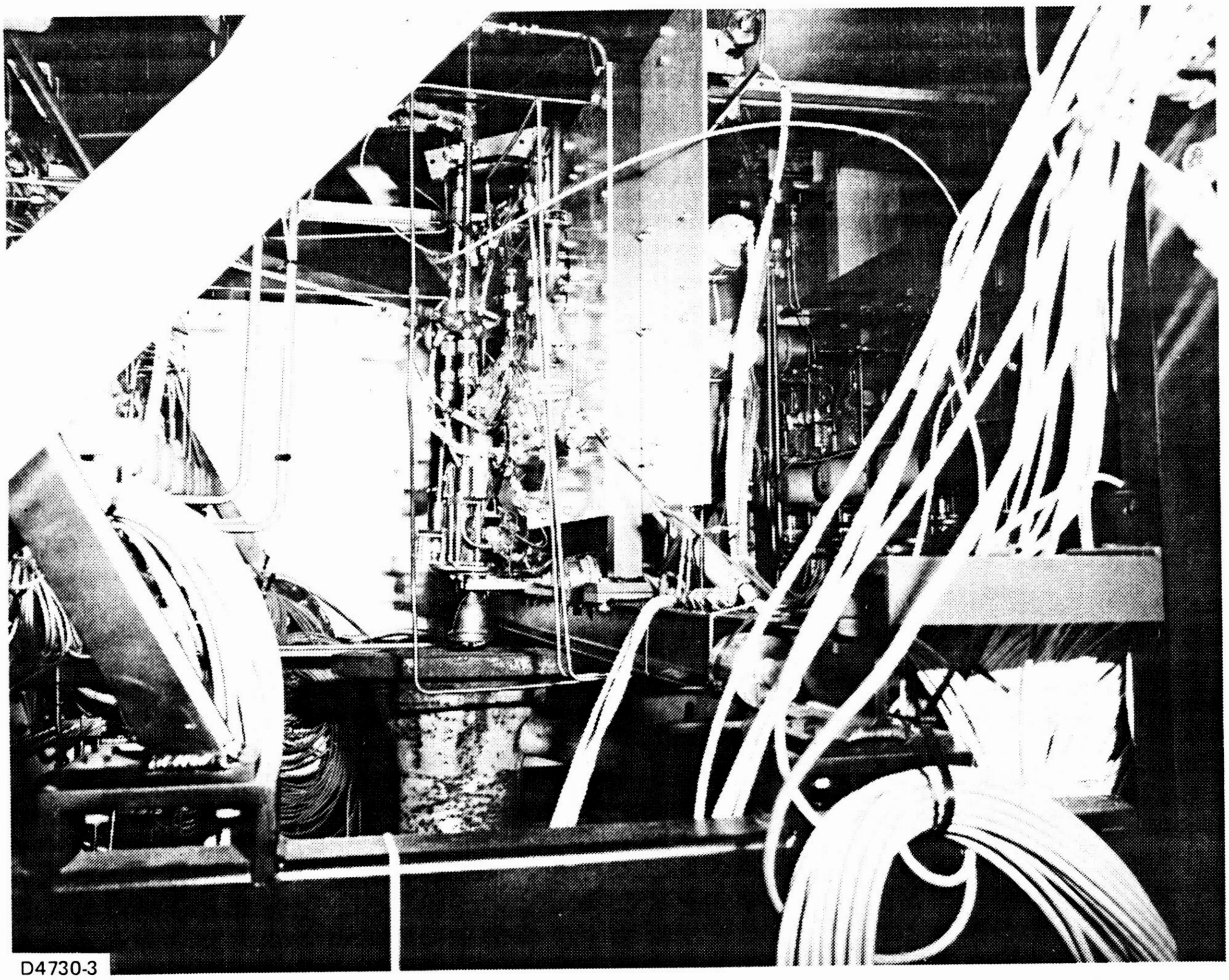

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Figure 5-11. Rocketdyne Prototype Thruster
in Test Bed for Initial Testing

The results of the specific impulse modeling predictions, based on the prototype measured C* performance, are shown in Figure 5-12. The JANNAF prediction indicates a specific impulse of 406 s and 346 s at mixture ratios of 3 and 8, respectively. The Rocketdyne boundary layer loss model predicts a 7 s loss over the mixture ratio range. The predicted curve intersecting 345 s at MR = 8 (minimum requirement) has been used in performance graphs as a reference (Figure 5-13). The corresponding thrust coefficient and theoretical C* prediction are shown in Figure 5-14.

Specific impulse calculated from the test bed thrust data, corrected for thrust data scatter using procedures described in Reference 1, are presented in Figure 5-15 for the prototype injector installed in the LeRC 2 thrust chamber. The thruster corrected specific impulse data are presented at a time slice of approximately 20 s. The data follow the predicted curve quite well.

Figure 5-16 displays a typical start and shutdown sequence that can be expected from the 25-lbf thruster. The test data verified that a specific impulse of 380 s at an operating mixture ratio of 8 can reasonably be expected form a flight-type thruster design. Reference 1 contains a complete discussion of thruster performance parameters and characteristics.

5.3 ELECTROLYSIS MODULE TESTING

With the addition of water electrolysis to the baseline space station system as the propellant supply, the need for an electrolysis system operation on the test bed became apparent. An electrolysis module was designed and fabricated at Rocketdyne to fit on top of the existing test bed propulsion module cube. Major components tested on the module include Arde steel tanks, SCI graphite wrapped tanks, a LSI electrolysis unit, and a HSD electrolysis unit.

The module also included canisters to contain each of the available WEUs because they were not operable in a vacuum. Molecular-sieve dryers designed by Boeing and fabricated at MSFC and moisture analyzers supplied by Martin were also included on the module.

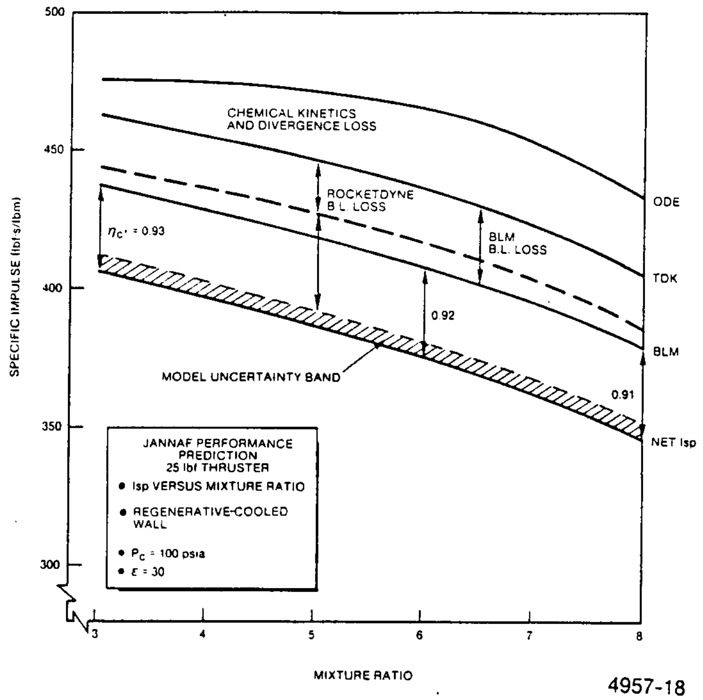

Figure 5-12. Specific Impulse Performance

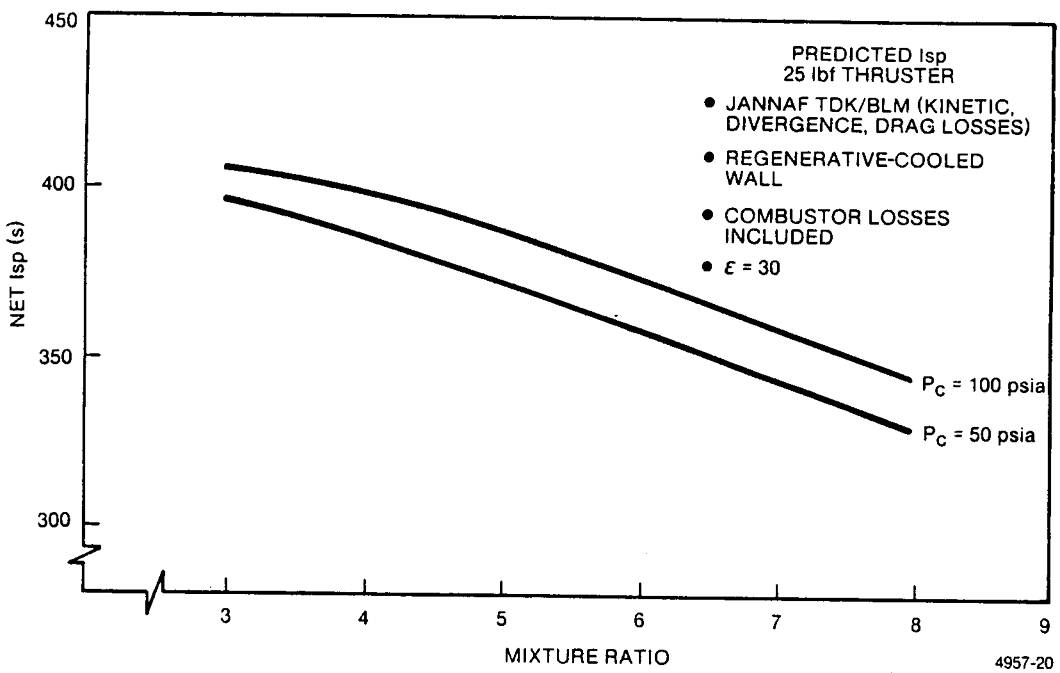

Figure 5-13. Effect of Chamber Pressure on Predicted Specific Impulse

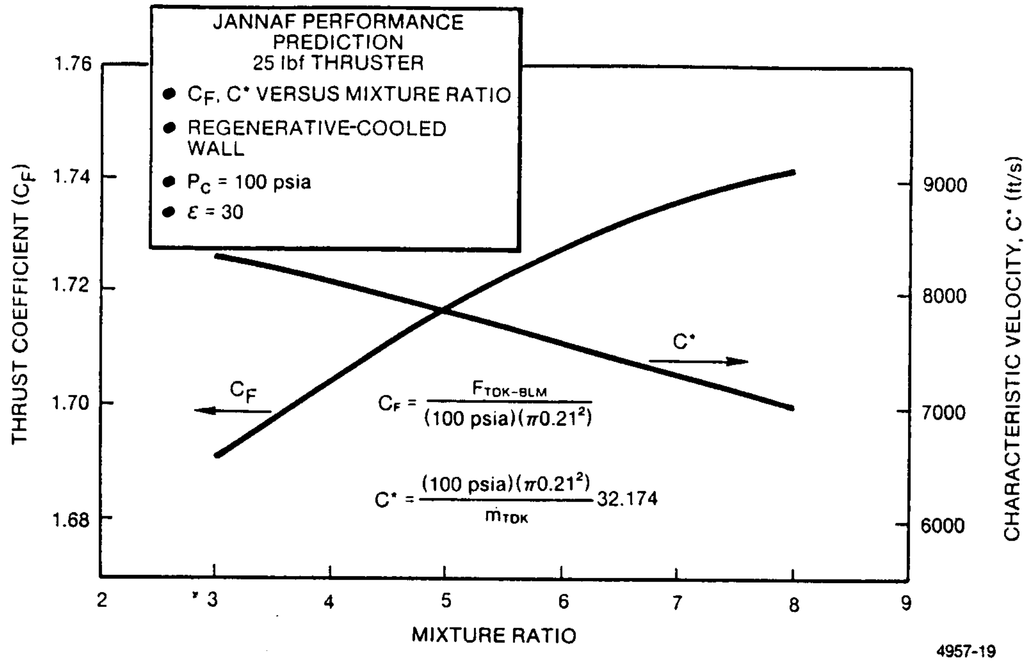

Figure 5-14. Thrust Coefficient and C* Versus Mixture Ratio

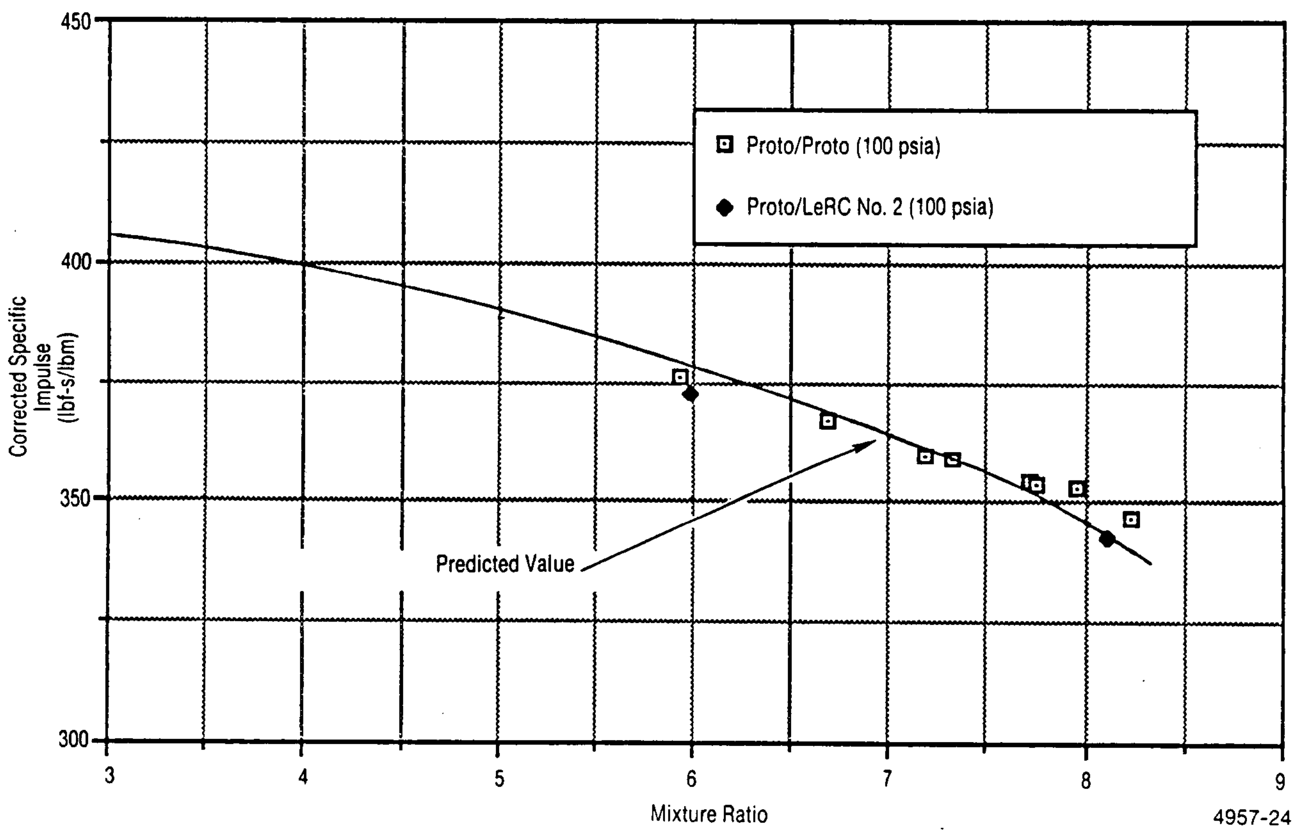

Figure 5-15. 25-lbf Thruster - Prototype Thruster Performance (20 s)

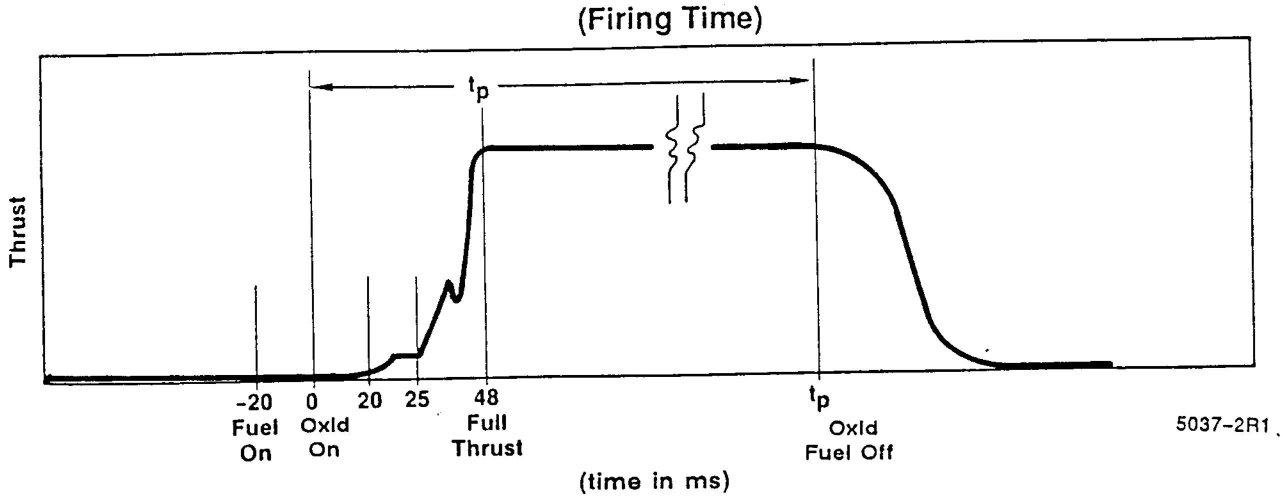

Figure 5-16. Typical Thruster Firing Profile

During electrolysis module tests, electrolysis operation was initiated by a test bed controller system command to the electrolysis unit controller. Following an electrolysis transition period, oxygen and hydrogen gas were generated. Table 5-2 shows the steady-state flow rates for the LSI 350-psia and HSD 1,000-psia systems. The hydrogen dryer saturates approximately twice as fast as the oxygen dryer (5.58 h versus 11.17 h). As a result of their higher saturation rate, the hydrogen dryers paced the primary and secondary dryer switching sequence. For example, during the LSI 350-psia test, the secondary dryer alternated into the system with the primary dryers in 6-h increments. During the 6 h that the secondary dryers were being saturated, the primary dryers were exposed to 450°F and vacuum. The primary and secondary dryers alternated into the system throughout test until the accumulators reached the electrolysis operating pressure, either 350 psia or 1,000 psia. At this point, the electrolysis units were powered down, the accumulators locked off, and the manifolds vented. A thruster test was subsequently performed utilizing the electrolysis-generated oxygen and hydrogen.

Data acquisition during test was totally automated. All control parameters except the electrolysis units were recorded on the control system. The electrolysis units were controlled via their own controllers which also monitored their parameters. The control system recorded data on hard disk for periodic dump to floppy disks during test or at the end of test. The LSI controller

Table 5-2. Summary of Dryer Saturation Performance as a Function of Product Gas Water Vapor Flow Rate

	LSI Unit						HSD Unit	
Product Gas	Minimum Flow (pph)	Time (h)	Design Flow (pph)	Time (h)	Maximum Flow (pph)	Time (h)	Maximum Flow (pph)	Time (h/d)
Oxygen	0.0001	20.1	0.0018	11.17	0.0029	6.93	0.00015	160.8/6.7
Hydrogen	0.0019	10.6	0.0036	5.58	0.0057	3.53	0.00031	77.8/3.24

Note: 1. LSI unit operating at 350 psia and 130°F.
2. HSD unit operating at 1,000 psia and 120°F.
3. Dryer saturation time = lb of absorbed water/100-lb MOL SIEVE + quantity of MOL SIEVE/moisture flow rate where lb of absorbed water/100-lb MOL SIEVE = 0.15 (LSI), 0.018 (HSD)

Quantity of MOL SIEVE = 1.34 lb

Moisture flow rate = function of operating point and product gas output.

recorded on a PC floppy disk, which was converted to an IBM format via a secondary disk. The frequency of disk changes is governed primarily by the controller sample rates. The HSD controller could line print and record on floppy disk via an IBM AT.

5.3.1 LSI Electrolysis Test Results

The test program resulted in the LSI unit operating for 70 h at the baseline operating conditions. Hydrogen production during the test was at a rate of 2.98×10^{-2} lb/h and with a total of 2.09 lb H_2 generated, while 16.54 lb O_2 were generated at an average production rate of 0.236 lb/h. The H_2 storage tank reached a pressure of 160.4 psia while the O_2 storage tank pressure reached 150.9 psia.

During the LSI testing, the longest continuous run was 60 h from 4:30 a.m. on 07/28/87 to 4 p.m. on 07/30/87. A series of plots are provided to depict SFE test data.

a. Figure 5-17 depicts the module voltage (E13) versus time in the test. Total average voltage for the twelve cell module remained stable at 19.7 V.

b. Figure 5-18 depicts the feedwater circulation loop temperature (T1) and module temperature (T2) versus time in the test. Average feedwater loop temperature was 136°F.

c. Figure 5-19 depicts the feedwater pressure (P3) and system pressure (P1) versus time in the test.

d. Figure 5-20 depicts the O_2 to H_2 differential pressure (P2) versus time in the test. The graph shows that two large swings in delta P occurred between 12 a.m. and 6 a.m. on 07/29/87. These large delta Ps correspond to water tank fills. It is suspected that the facility N_2 supply pressure regulator may have begun to malfunction at this time.

After completion of the test, the unit was removed from the test chamber and shipped back to LSI for thorough posttest evaluation. The unit was checkout tested at LSI from 11 September 1987 through 16 September 1987 for a total of 140 h of continuous operation. Module performance was normal.

The SFE performed as designed producing H_2 and O_2 at its design rate of 2.98 and 10^{-2}lb/h of H_2 and 0.236 lb/h of O_2 while operating at 315 psia. The tests were successful in demonstrating the unit as applied to the production of the O_2/H_2 propellant gases for space station propulsion.

5.3.2 HSD Electrolysis Test Results

The testing of the HSD electrolysis system was a demonstration of the end-to-end SSPS. All elements of the system functioned including firing of the thruster using the electrolysis products stored in the tankage provided. The structural composite graphite filament-wound tanks were used to accumulate the

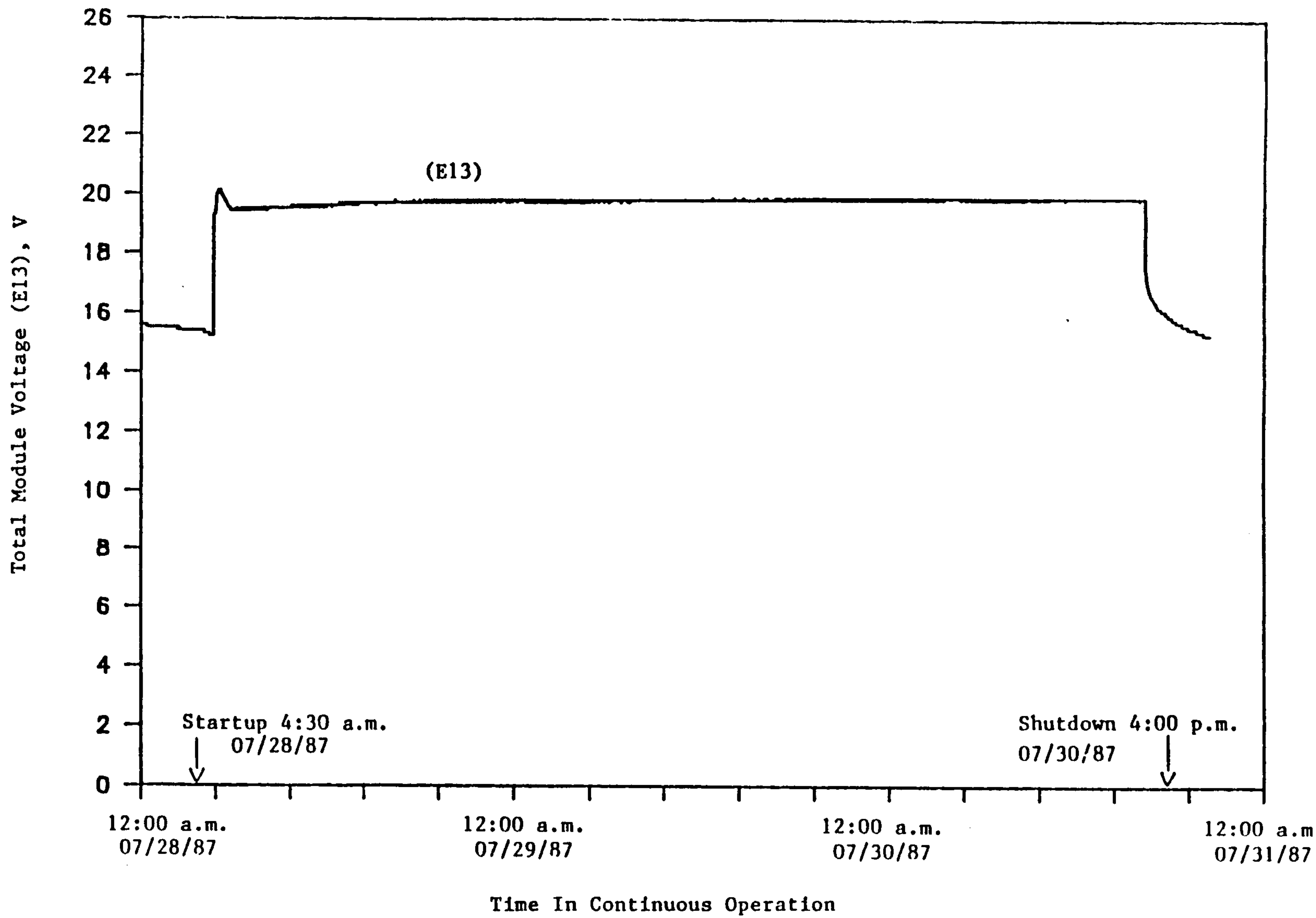

Figure 5-17. SFE Module Voltage (E13) Versus Time in SSPTB Test 07/28/87 through 07/30/87

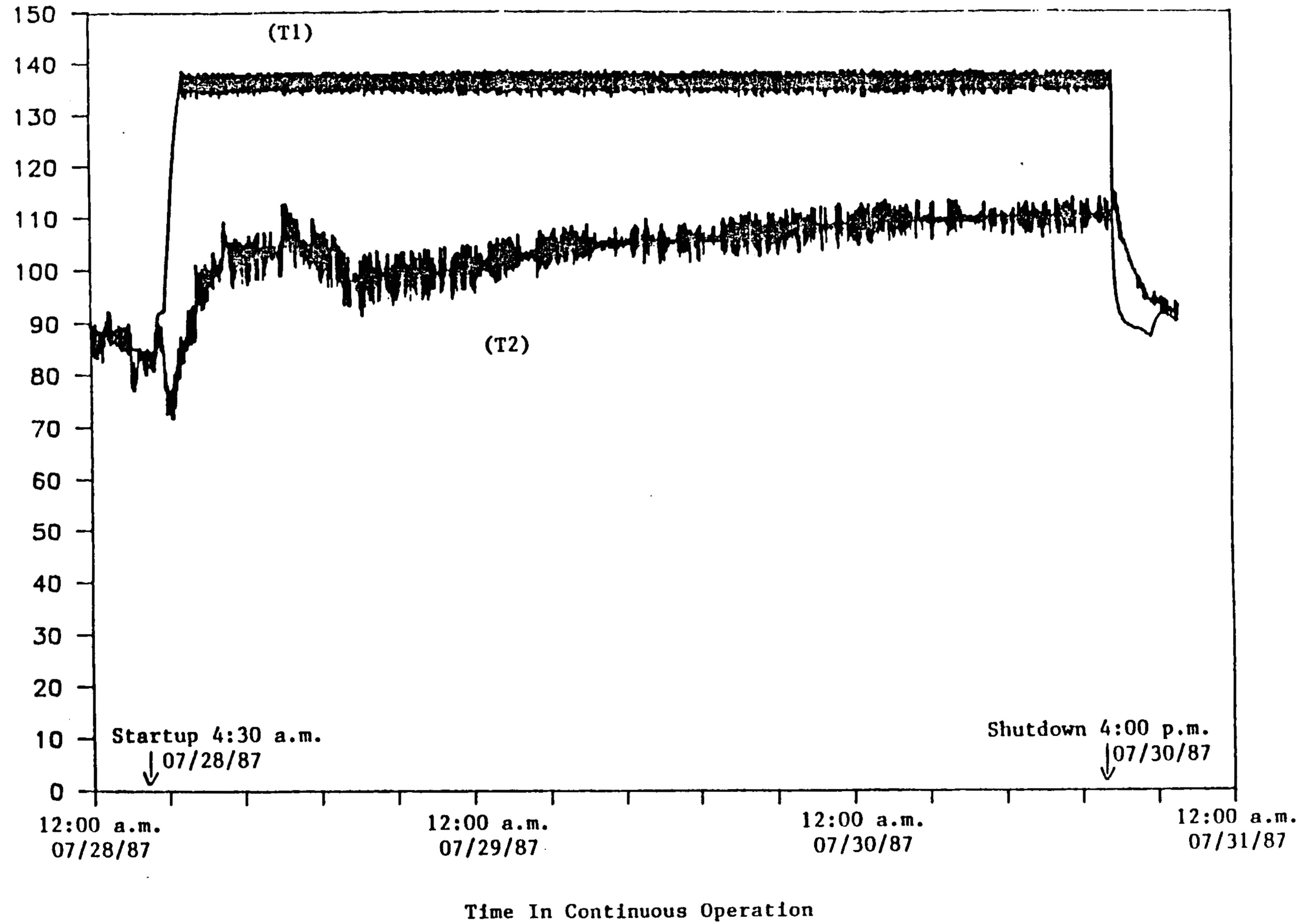

Figure 5-18. SFE Feedwater Circulation Loop Temperature (T1) and Module Temperature (T2) Versus Time in SSPTB Test 07/28/87 through 07/30/87

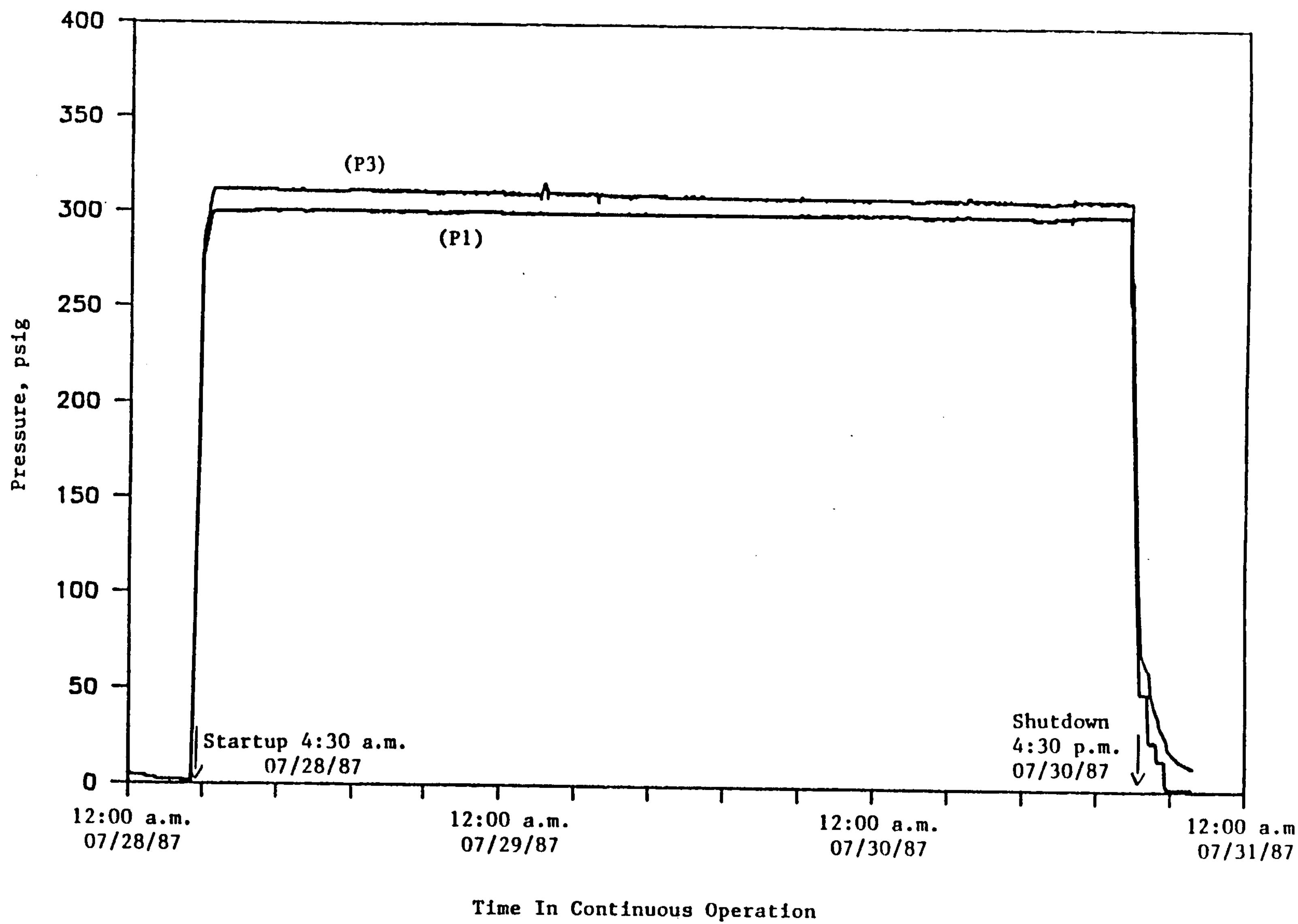

Figure 5-19. SFE Feedwater Pressure (P3) and System Pressure (P1) Versus Time in SSPTB Test 07/28/87 through 07/30/87

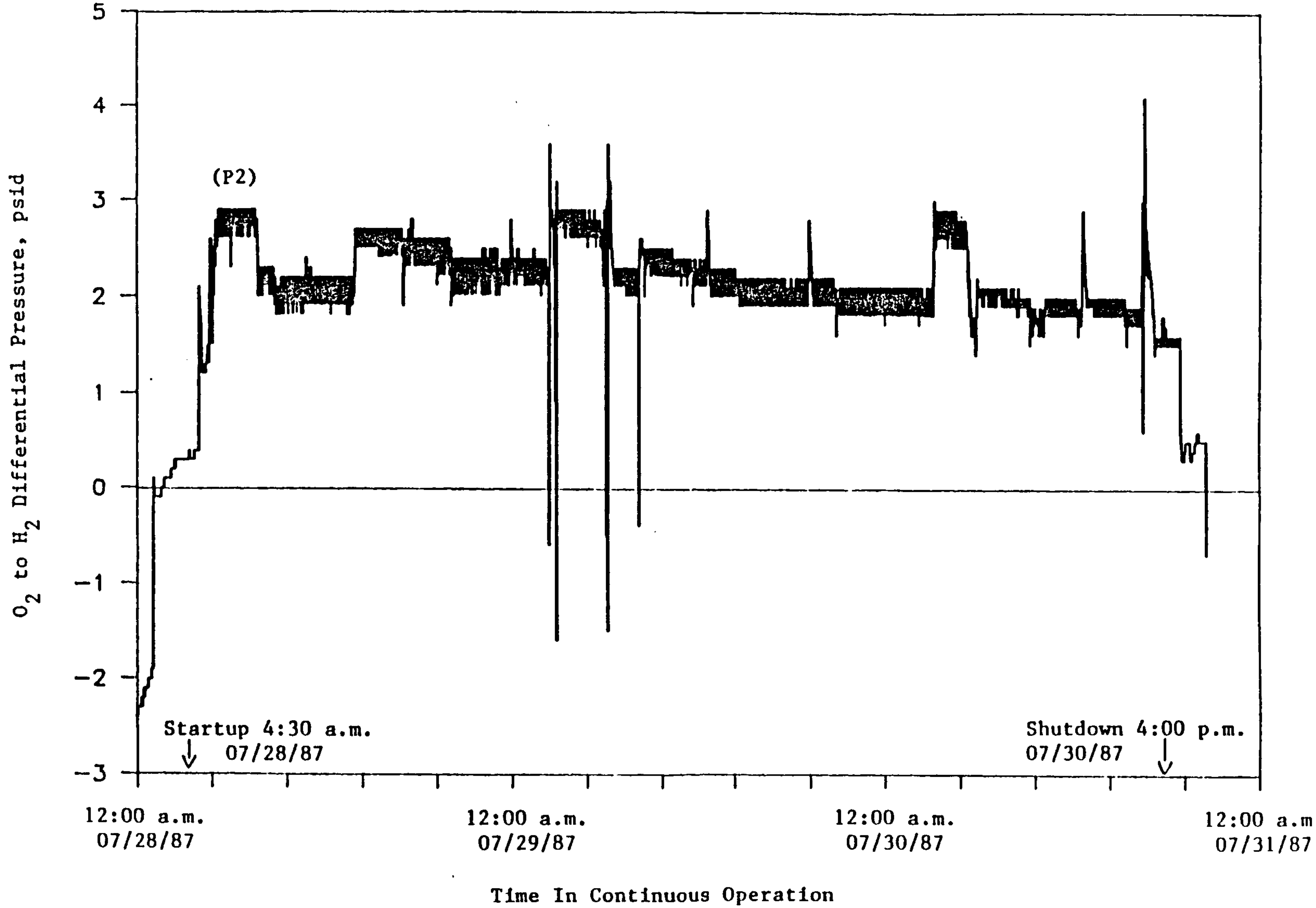

Figure 5-20. SFE O_2 to H_2 Differential Pressure (P2) Versus Time in SSPTB Test 07/28/87 through 07/30/87

gases. Figure 5-21 displays the tank pressures for the oxygen and hydrogen as a function of time. The events listed refer to Table 5-3. Testing began on 17 November 1987 and continued around the clock until 25 November 1987, at which time the tests were terminated for the Thanksgiving holidays. The hydrogen and oxygen tank pressure had risen to 721 psia and 661 psia respectively.

At the time of test termination 13,125 min had elapsed since test start. During this period 11 shutdown or standby periods, for a total of 1,898 min, had occurred as summarized in Table 5-3. A total run time of 11,227 min or 7 d, 19 h, 7 min of successful system operation had been logged for the electrolysis system.

The accumulated tank pressures decayed slightly to 676 psia for the hydrogen and 610 psia for the oxygen from 25 November till 1 December 1987. To continue operation with the electrolysis unit with leakage occurring was not considered feasible. The leakage would have precluded the system from reaching the 1,000 psia objective. To verify thruster operations with the electrolysis-generated gases, a thruster test was performed. Test 103-091 was successfully carried out at a mixture ratio of 8 and a chamber pressure of 100 psia for 175 s. No performance or operation deviations were noted.

Subsequent to the thruster firing, the plumbing leaks were repaired and the accumulators were recharged. Electrolysis operation was resumed on 2 December 1987 at 9:15 p.m. with an objective of completing the high-pressure (nominal 1,000 psia) electrolysis system operation demonstration. The testing was terminated on 3 December 1987 at 11:48 a.m. with 925 psia in the hydrogen tank (the targeted valve) and 865 psia in the oxygen tank. A total of 873 min had elapsed with no shutdown or standby time accrued.

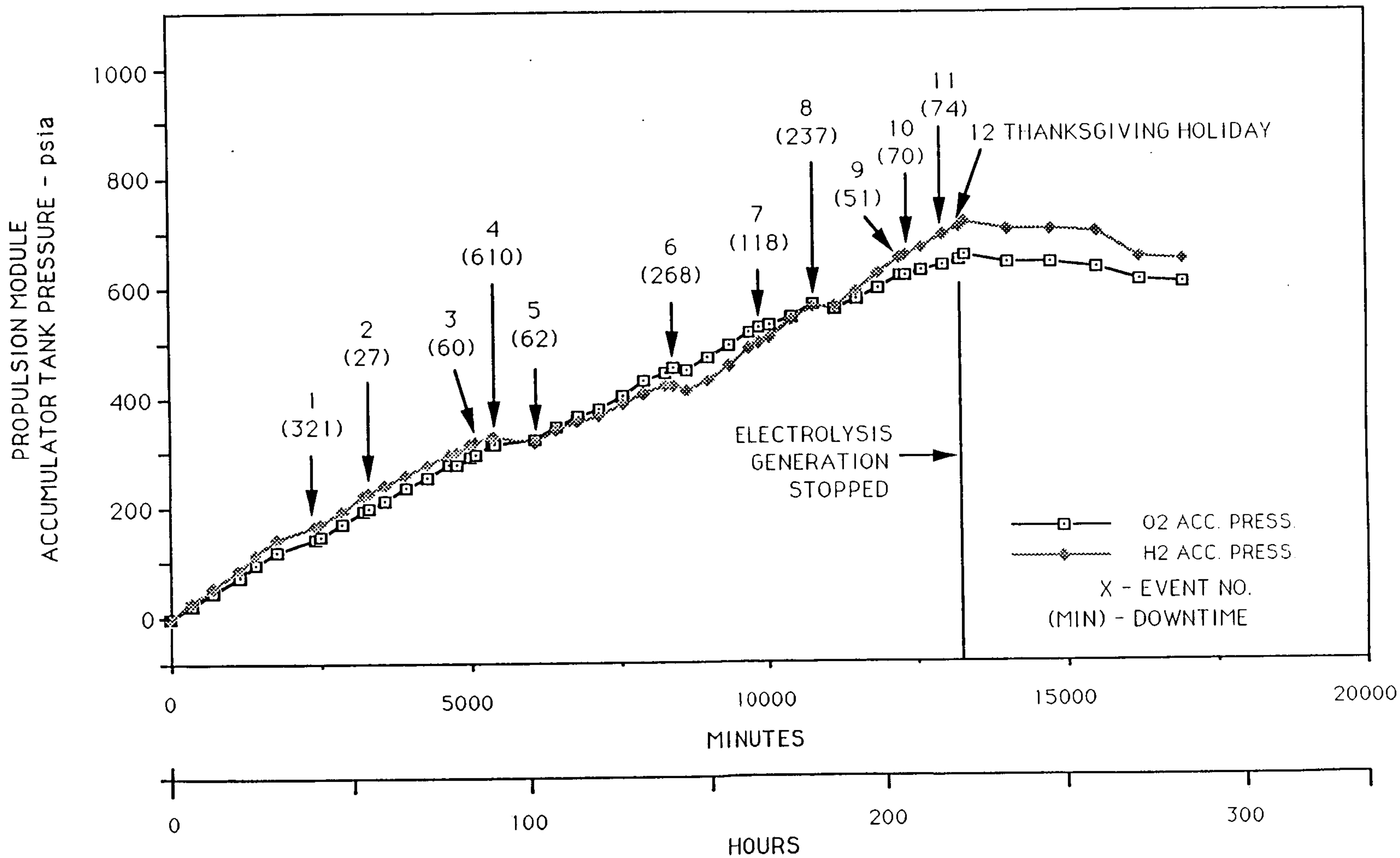

Figure 5-21. HSD Electrolysis System Test Results
(Test 084)

Table 5-3. HSD Electrolysis Test Shutdown/Standby Summary (P103-084)

EVENT NO.	DAY DATE	TEST DAY	DOWN TIME (REAL TIME) FROM	DOWN TIME (REAL TIME) TO	DOWN TIME (TEST TIME) FROM	DOWN TIME (TEST TIME) TO	COMMENTS	DOWN TIME	Σ DOWN TIME
1	TUES 11/17	~1.5	6:22p	11:43a	2162	2483	SHUTDOWN - TRS 80 ACCIDENTLY TURNED OFF	321	321
2	WED 11/18	~2	2:20p	2:47p	3360	3387	STANDBY - HSD WATER FILL (NOT RESET CORRECTLY FROM PREVIOUS SHUTDOWN)	27	348
3	THU 11/19	~3.5	1:45p	2:45p	4765	4825	STANDBY - HSD CELL VOLTAGE NEAR R/L (V4)	60	408
4	FRI 11/20	~4	2:50a	1:00p	5550	6160	SHUTDOWN - DG DELTA TIME REACHED MAX LEAK CHECKS, H90 REPLACED	610	1018
5	FRI 11/20	~4	1:15p	2:17p	6175	6237	STANDBY - LEAK CHECKS	62	1080
6	SUN 11/22	~4	2:00a	6:28a	8380	8648	STANDBY - DG DATA TRANSFER	268	1348
7	MON 11/23	~6.5	4:00a	5:58a	9940	10058	STANDBY - HSD CELL VOLTAGE NEAR R/L (V4)	118	1466
8	MON 11/23	~7	7:15p	11:12p	10855	11092	SHUTDOWN - DG, ANOTHER DATA FILE STARTED, HSD SHUTDOWN RESTART REQUIRED PURGE	237	1703
9	TUE 11/24	~8.5	3:57p	4:48p	12097	12148	STANDBY - HSD CELL VOLTAGE NEAR R/L (V4)	51	1754
10	TUE 11/24	~8.5	10:05p	11:15p	12465	12535	STANDBY - HSD CELL VOLTAGE NEAR R/L (V4)	70	1824
11	WED 11/25	~9	5:01a	6:15a	12881	12955	STANDBY - HSD CELL VOLTAGE NEAR R/L (V4)	74	1898
12	WED 11/25	~9	9:05a	-	13125	-	SHUTDOWN - HOLIDAY	-	-

TOTAL TEST TIME ... 13125
TOTAL DOWN TIME ... 1898
TOTAL RUN TIME 11227 (7d,19h,7m)

A total of 8 d, 9 h, 40 min of electrolysis unit and system operation had been accrued on the HSD electrolysis system. The hydrogen and oxygen gases were accumulated to 925 psia and 865 psia respectively. A 175 s thruster firing was performed using the products of electrolysis with no performance or operational deviations observable. The electrolysis testing was considered successful and to have met the objectives of demonstrating operation up to 1,000 psia.

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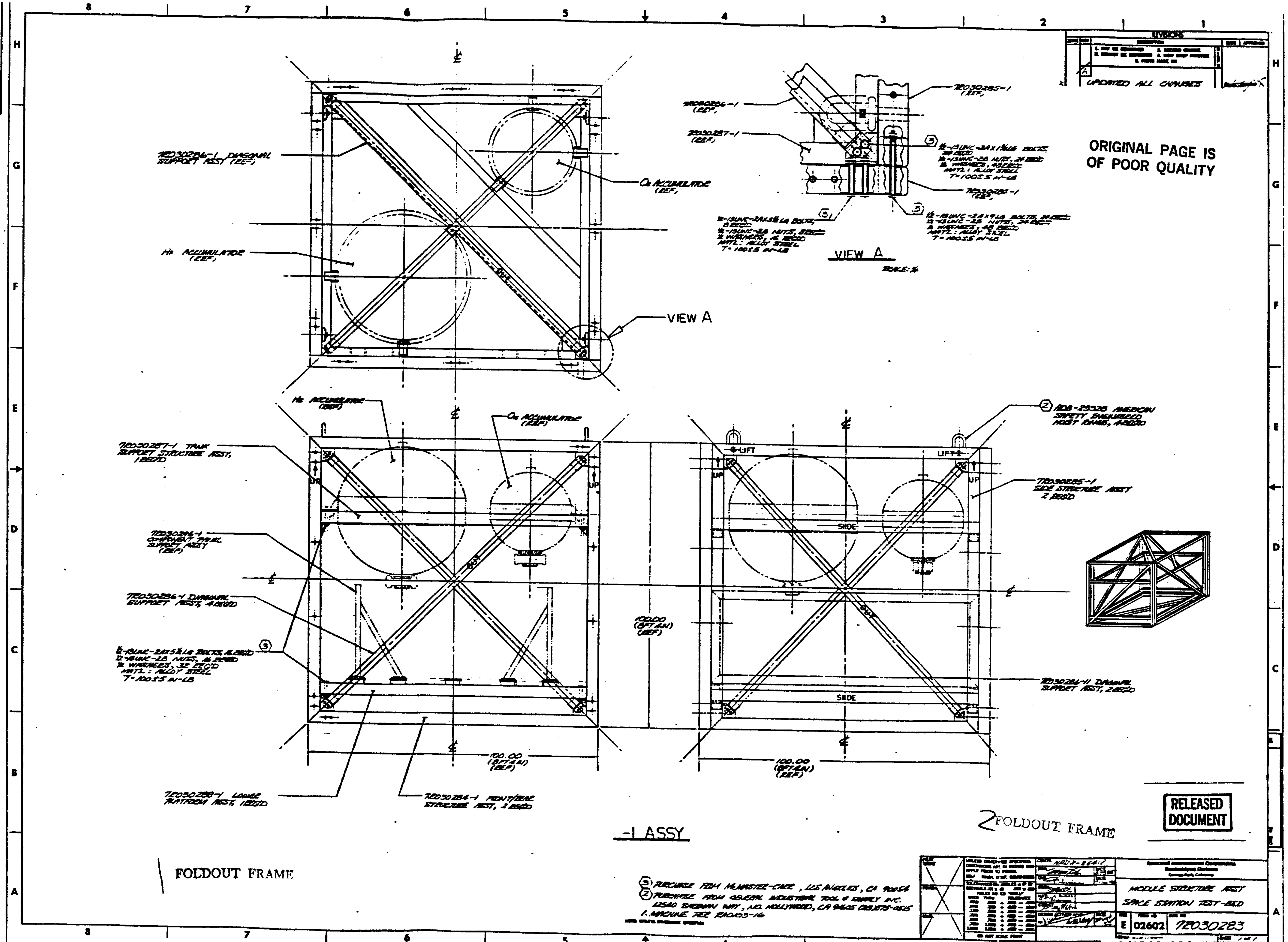
APPENDIX A

The major component and assembly drawings created for fabrication and assembly of the test bed are included in this appendix. The appendix is divided into three sections, the propulsion module, the electrolysis module, and the thrust measurement system. The drawings are arranged in numerical order.

Section A-1. This section contains all the drawings necessary for the assembly of the propulsion module. The drawings are listed in Table A-1.

Table A-1. Propulsion Module Drawings

- 7R030295 Accumulator Module Assembly
    - 7R030294 Schematic
    - 45454 Oxygen Accumulator
    - 45455 Hydrogen Accumulator
    - 7R030291 Control Assembly - H_2/O_2
        - 7R030289 Control Panel - H_2/O_2
    - 7R030292 Control Panel Assembly - Resistojet
        - 7R030290 Control Panel - Resistojet
    - 7R032252 Installation Test Bed Computer Control System Assembly
    - 7R032251 Instrumentation/Control Assembly
    - 7R032250 Instrumentation Cabling
    - 7R032248 Instrumentation Box Assembly
    - 7R032249 Control Box Assembly
    - 7R030283 Module Structure Assembly
        - 7R030293 Thruster/Resistojet Support Assembly
        - 7R030296 Component Panel Support Assembly
        - 7R030297 Resistojet Component Panel Support Assembly
        - 7R032247 RCS Support Bracket Assembly
        - 7R030284 Front/Rear Structure Assembly
        - 7R030285 Side Structure Assembly
        - 7R030286 Diagonal Support Assembly
        - 7R030287 Tank Support Structure Assembly
        - 7R030288 Lower Platform Assembly



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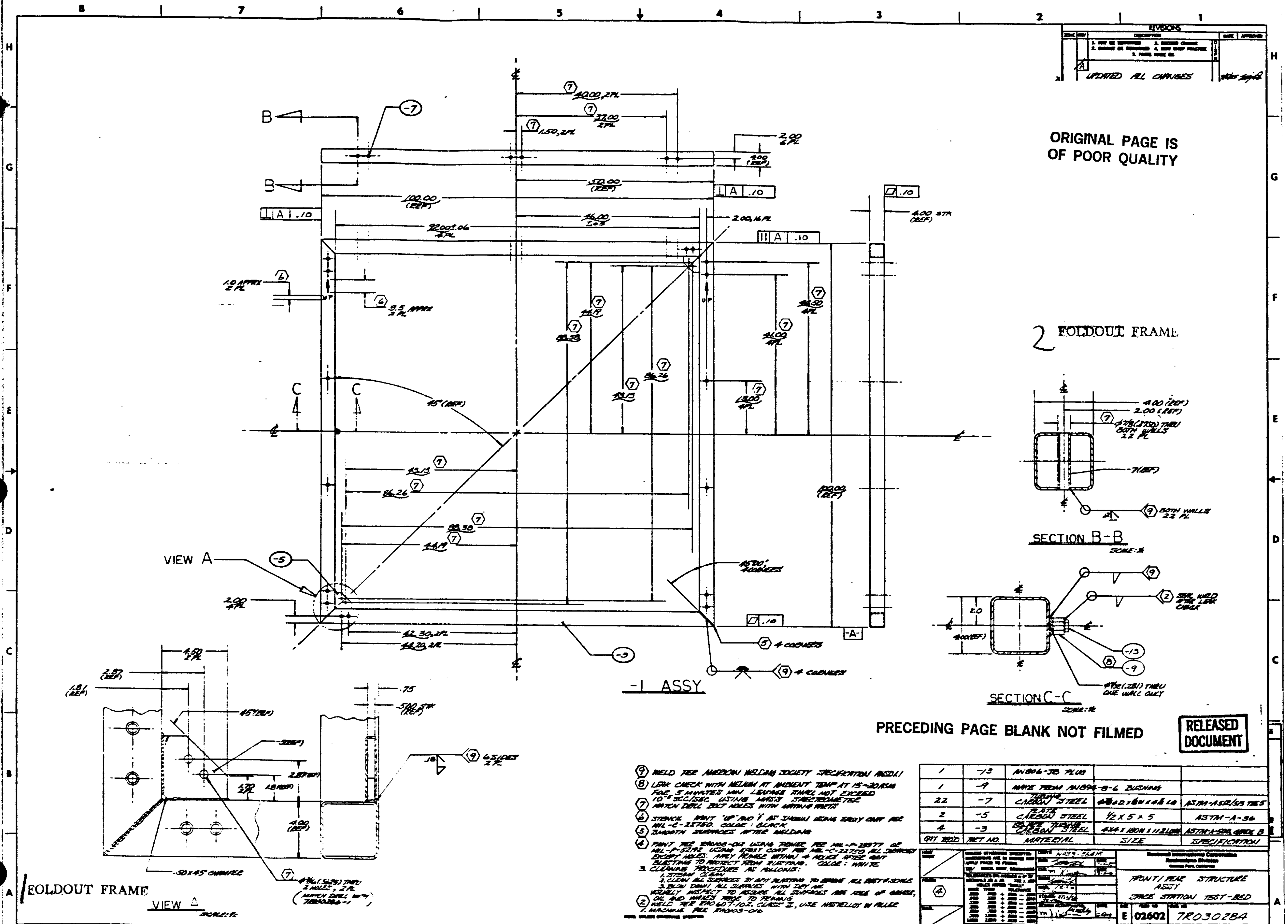
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SECTION B-B
SECTION C-C
-1 ASSY
VIEW A
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VIEW A
4 CORNERS
BOTH WALLS 22 PL
.50 X 45° CHAMFER
QTY REQD | PART NO. | MATERIAL | SIZE | SPECIFICATION
1 | -13 | AN806-J8 PLUG
1 | -9 | MAKE FROM AN894-B-6 BUSHING
22 | -7 | TUBING CARBON STEEL | ASTM-A-513/513 TIES
2 | -5 | PLATE CARBON STEEL | 1/2 X 5 X 5 | ASTM-A-36
4 | -3 | CARBON STEEL | ASTM-A-500 GRADE B
FRONT/REAR STRUCTURE ASSY
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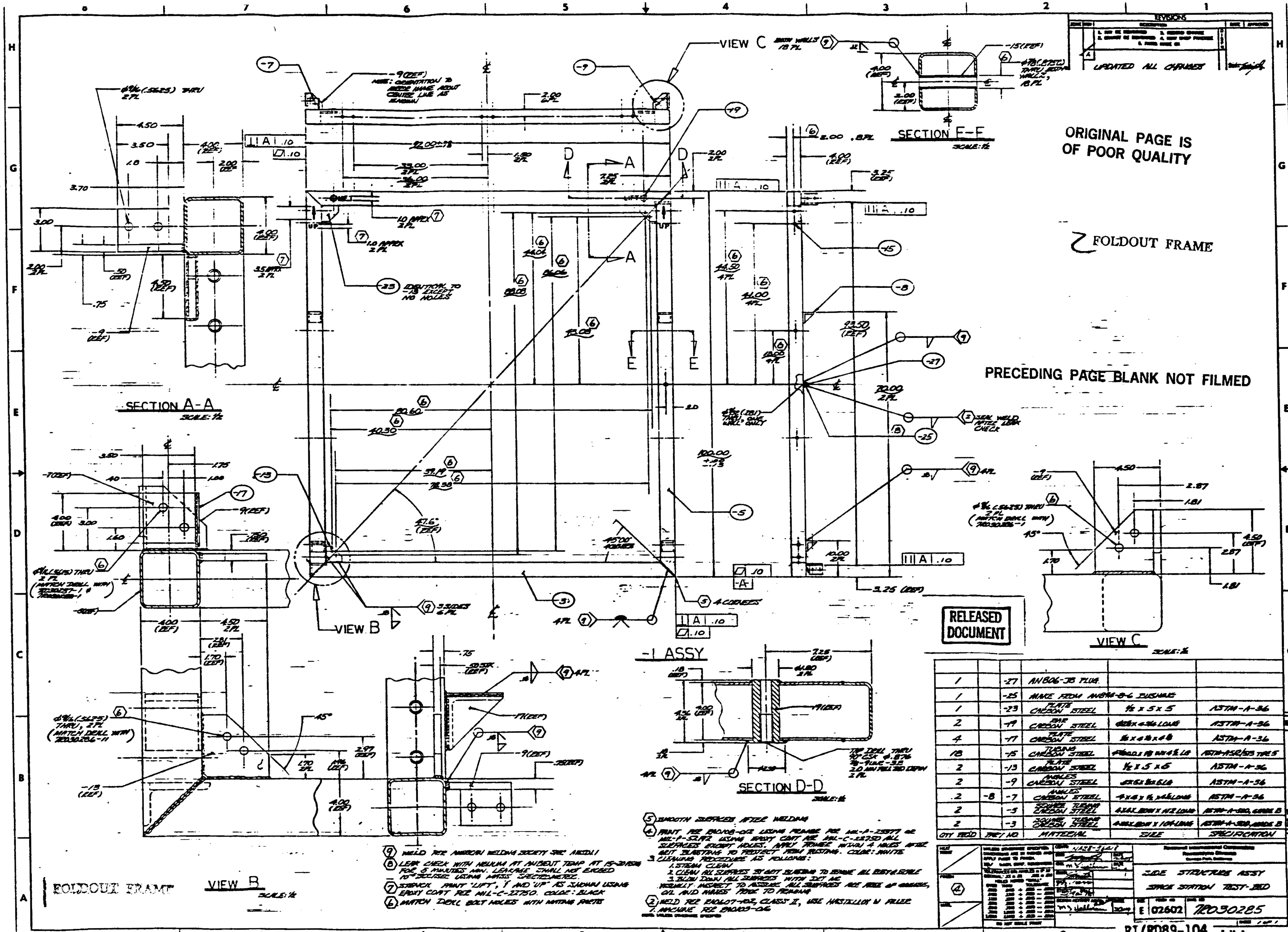

QTY REQD	PART NO.		MATERIAL	SIZE	SPECIFICATION
1		-27	AN806-?? PLUG		
1		-25	MAKE FROM AN894-?-6 BUSHING		
1		-23	PLATE CARBON STEEL	1/2 x 5 x 5	ASTM-A-36
2		-19	BAR CARBON STEEL	[illegible] x 4.96 LONG	ASTM-A-36
4		-17	PLATE CARBON STEEL	[illegible]	ASTM-A-36
18		-15	TUBING CARBON STEEL	[illegible]	ASTM-A513 TYPE 5
2		-13	PLATE CARBON STEEL	1/2 x 5 x 6	ASTM-A-36
2		-9	CARBON STEEL	[illegible]	ASTM-A-36
2	-8	-7	ANGLES CARBON STEEL	4 x 4 x 1/2 x [illegible] LONG	ASTM-A-36
2		-5	SQUARE TUBING CARBON STEEL	[illegible]	ASTM-A-500, GRADE B
2		-3	SQUARE TUBING CARBON STEEL	[illegible]	ASTM-A-500, GRADE B

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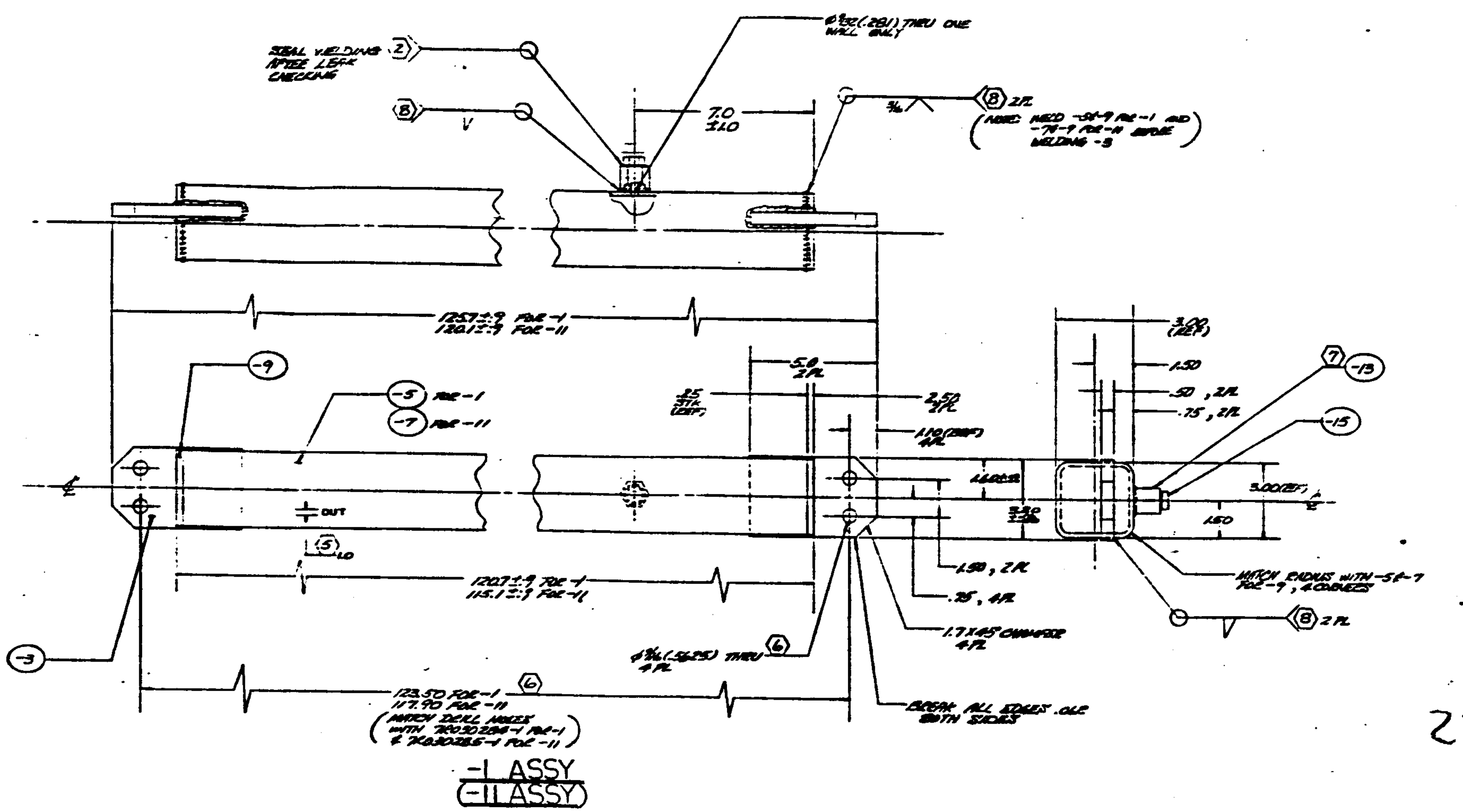

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1	1	-15	AN806-3B PLUG		
1	1	-13	MAKE FROM AN894-8-6 BUSHING		
2	2	-9	END PLATE	CARBON STL	ASTM-A-36
1		-7	SQUARE TUBING	CARBON STL	
	1	-5	SQUARE TUBING	CARBON STL	
2	2	-3	END PLATE	CARBON STL	ASTM-A-36
-11	-1	7R030286			
QTY REQD	QTY REQD	PART NO	DESCRIPTION	MATERIAL	SPECIFICATION

8. WELD PER AMERICAN WELDING SOCIETY SPECIFICATION ANSI D1.1
7. LEAK CHECK WITH HELIUM AT AMBIENT TEMP AT 15-20 PSIG FOR 5 MINUTES MINIMUM. LEAKAGE SHALL NOT EXCEED 10^{-4} SCC/SEC USING MASS SPECTROMETER.
6. MATCH DRILL BOLT HOLES WITH MATING PARTS
5. STENCIL PAINT "OUT" AS SHOWN USING EPOXY COAT PER MIL-C-22750. COLOR: BLACK
4. PAINT PER 2A0108-02 USING PRIMER PER MIL-P-23377 OR MIL-P-52192 USING EPOXY COAT PER MIL-C-22750 ALL SURFACES EXCEPT HOLES. APPLY PRIMER WITHIN 4 HOURS AFTER GRIT BLASTING TO PROTECT FROM RUSTING. COLOR: WHITE
3. CLEANING PROCEDURE AS FOLLOWS:
   1. SYSTEM CLEAN
   2. CLEAN ALL SURFACES BY GRIT BLASTING TO REMOVE ALL RUST & SCALE
   3. BLOW DOWN ALL SURFACES WITH DRY AIR
   VISUALLY INSPECT TO ASSURE ALL SURFACES ARE FREE OF GREASE, OIL AND WATER PRIOR TO PRIMING
2. WELD PER 2A0607-102, CLASS II, USE HASTELLOY W FILLER
1. MACHINE PER 2A0103-06

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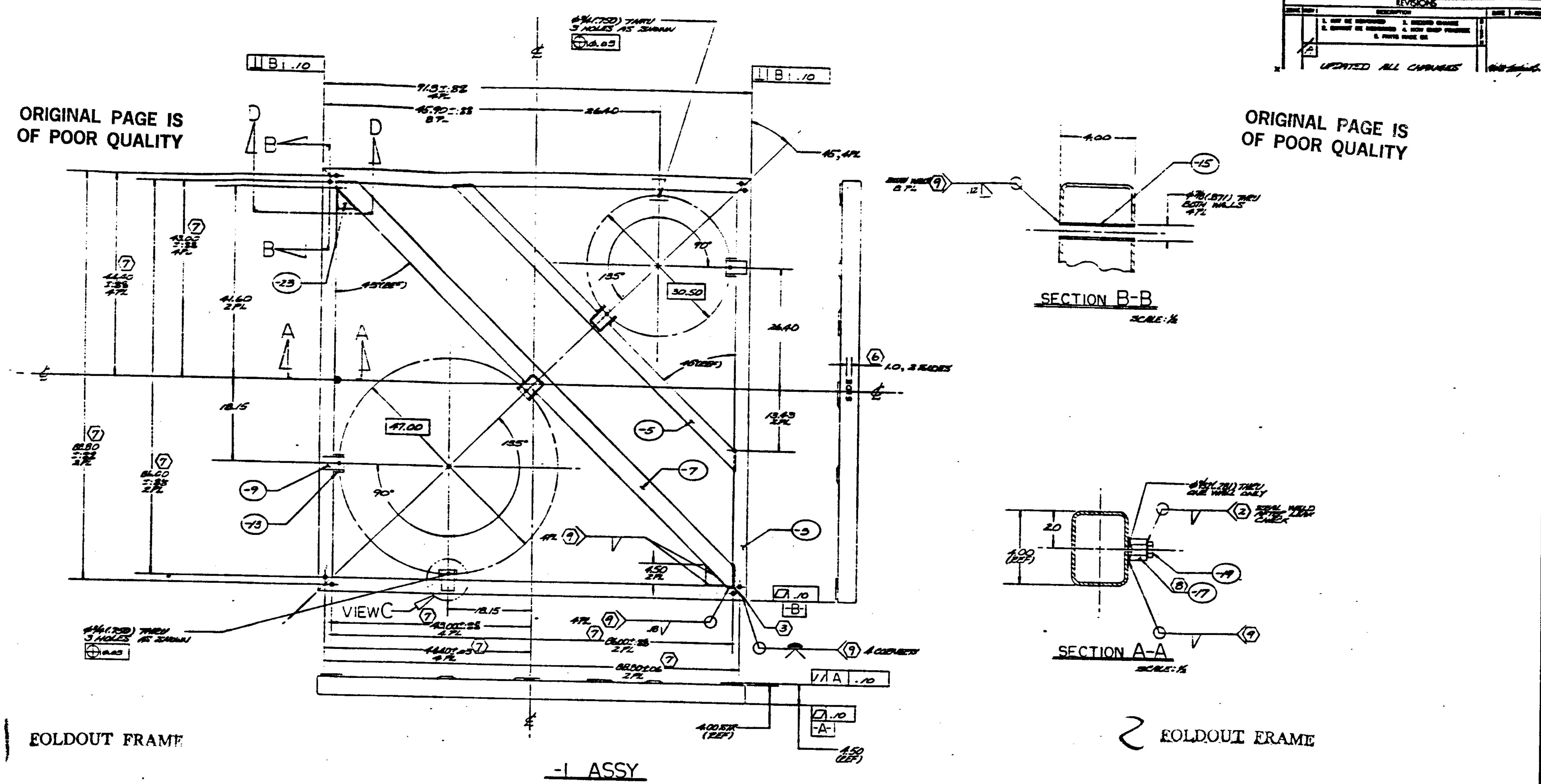

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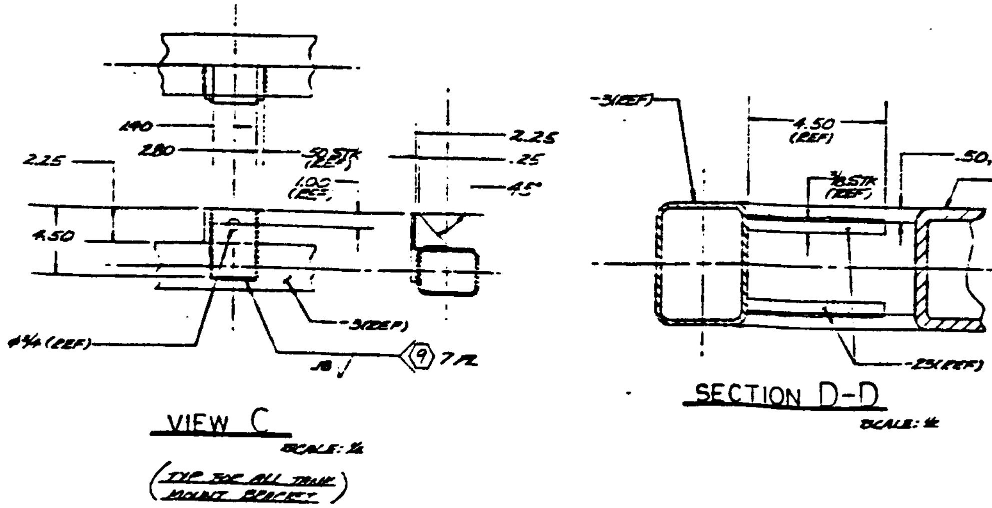

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9. WELD PER AMERICAN WELDING SOCIETY SPECIFICATION AWS D1.1
8. LEAK CHECK WITH HELIUM AT AMBIENT TEMP AT 15~20 PSIG FOR 5 MINUTES MIN. LEAKAGE SHALL NOT EXCEED 10^{-6} SCC/SEC USING MASS SPECTROMETER
7. MATCH DRILL WITH MATING PARTS
6. STENCIL PAINT "SIDE" AS SHOWN USING EPOXY COAT PER MIL-C-22750. COLOR: WHITE
5. PAINT PER RA0106-012 USING PRIMER PER MIL-P-23377 or MIL-P-52192 USING EPOXY COAT PER MIL-C-22750 ALL SURFACES EXCEPT HOLES. APPLY PRIMER WITHIN 4 HOURS AFTER GRIT BLASTING TO PROTECT FROM RUSTING. COLOR: BLACK
4. CLEANING PROCEDURE AS FOLLOWS:
   1. STEAM CLEAN
   2. CLEAN ALL SURFACES BY GRIT BLASTING TO REMOVE ALL RUST & SCALE
   3. BLOW DOWN ALL SURFACES WITH DRY AIR
   VISUAL INSPECTION TO ASSURE ALL SURFACES ARE FREE OF GREASE, OIL AND WAXES PRIOR TO PRIMING
3. SMOOTH SURFACES AFTER WELDING
2. WELD PER RA0607-102, CLASS II, USE HASTELLOY W FILLER
1. MACHINE PER RA0103-016

NOTES: UNLESS OTHERWISE SPECIFIED

QTY REQD	PART NO.	MATERIAL	SIZE	SPECIFICATION
4	-23	PLATE CARBON STEEL	⅜ x 5½ x 5½	ASTM-A-36
1	-19	AN806-J8 PLUG		
1	-17	MAKE FROM AN894-8-6 BUSHING		
8	-15	TUBING CARBON STEEL	[illegible]	ASTM-A513 TYPE 5
12	-13	PLATE CARBON STEEL	½ x 3 x 3	ASTM-A-36
6	-9	PLATE CARBON STEEL	½ x 3⅜ x 5	ASTM-A-36
1	-7	RECTANGULAR TUBING CARBON STEEL	4 x 4 x ¼ W x 128 LG	ASTM-A-500, GRADE B
1	-5	RECTANGULAR TUBING CARBON STEEL	4 x 3 x ¼ W x 90 LG	ASTM-A-500, GRADE B
4	-3	RECTANGULAR TUBING CARBON STEEL	4 x 3 x ¼ W x 100 LG	ASTM-A-500, GRADE B

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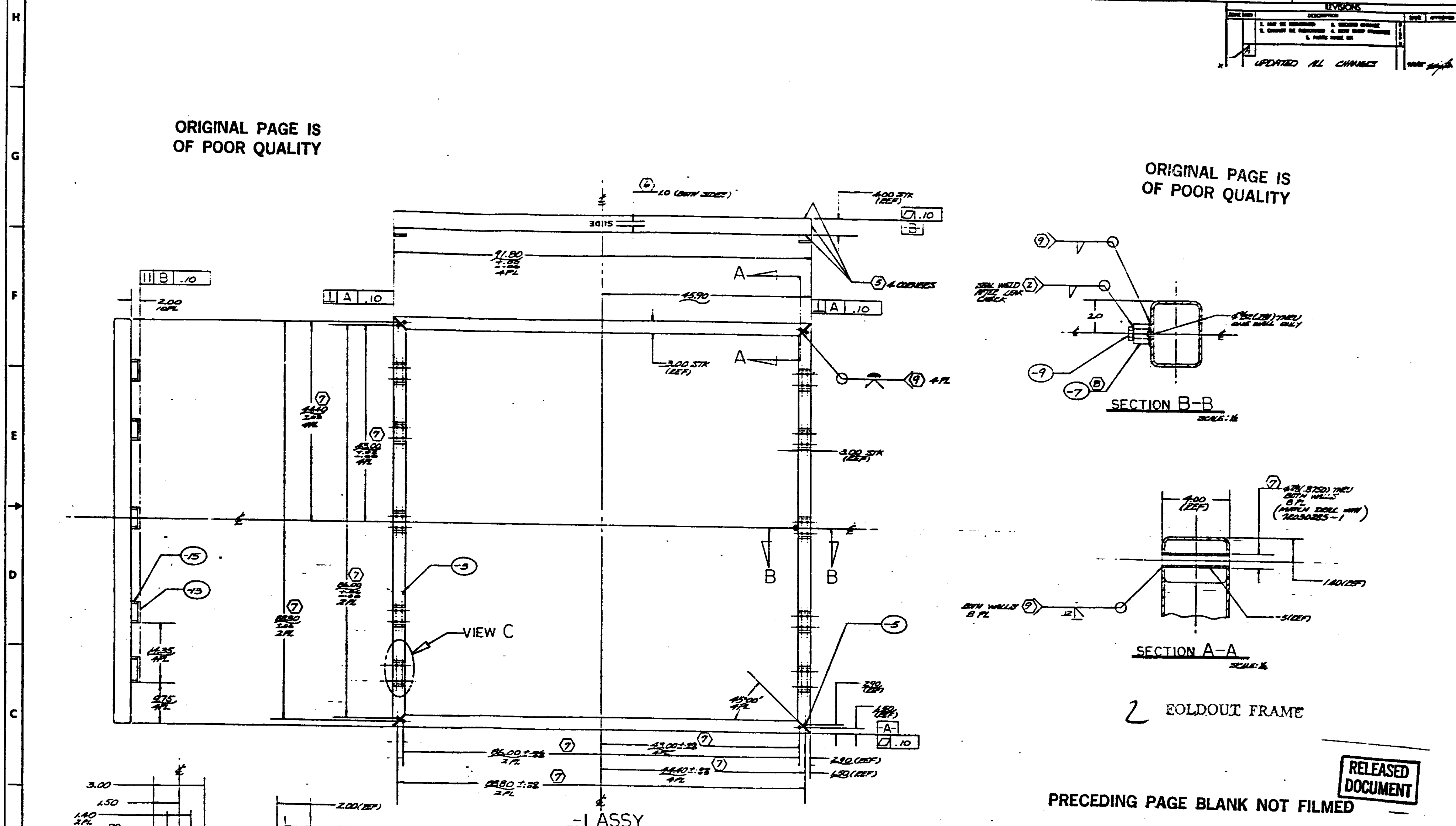

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9. WELD PER AMERICAN WELDING SOCIETY SPECIFICATION ANSD1.1
8. LEAK CHECK WITH HELIUM AT AMBIENT TEMP. AT 15~20 PSIG FOR 5 MINUTES MIN. LEAKAGE SHALL NOT EXCEED 10^{-5} SCC/SEC USING MASS SPECTROMETER
7. MATCH DRILL BOLT HOLES WITH MATING PARTS
6. STENCIL PAINT "SIDE" AS SHOWN USING EPOXY COAT PER MIL-C-22750. COLOR: WHITE
5. SMOOTH SURFACES AFTER WELDING
4. PAINT PER RA0408-012 USING PRIMER PER MIL-P-23377 OR MIL-P-52192 USING EPOXY COAT PER MIL-C-22750 ALL SURFACES EXCEPT HOLES. APPLY PRIMER WITHIN 4 HOURS AFTER GRIT BLASTING TO PROTECT FROM RUSTING. COLOR: BLACK
3. CLEANING PROCEDURE AS FOLLOWS:
   1. STEAM CLEAN
   2. CLEAN ALL SURFACES BY GRIT BLASTING TO REMOVE ALL RUST & SCALE
   3. BLOW DOWN ALL SURFACES WITH DRY AIR
   VISUALLY INSPECT TO ASSURE ALL SURFACES ARE FREE OF GREASE, OIL AND WAXES PRIOR TO PRIMING
2. WELD PER RA0607-102, CLASS I, USE HASTELLOY W FILLER
1. MACHINE PER RA0003-06

NOTE: UNLESS OTHERWISE SPECIFIED

QTY REQD	PART NO.	MATERIAL	SIZE	SPECIFICATION
20	-15	PLATE CARBON STEEL	½ x 2 x 3½	ASTM-A-36
10	-13	PLATE CARBON STEEL	½ x 3½ x 6	ASTM-A-36
1	-9	AN806-18 PLUG		
1	-7	MAKE FROM AN894-8-6 BUSHING		
8	-5	TUBING CARBON STEEL	[illegible]	ASTM-A513 [illegible] TYPE 5
4	-3	RECTANGULAR TUBING CARBON STEEL	[illegible]	ASTM-A-500, GRADE B

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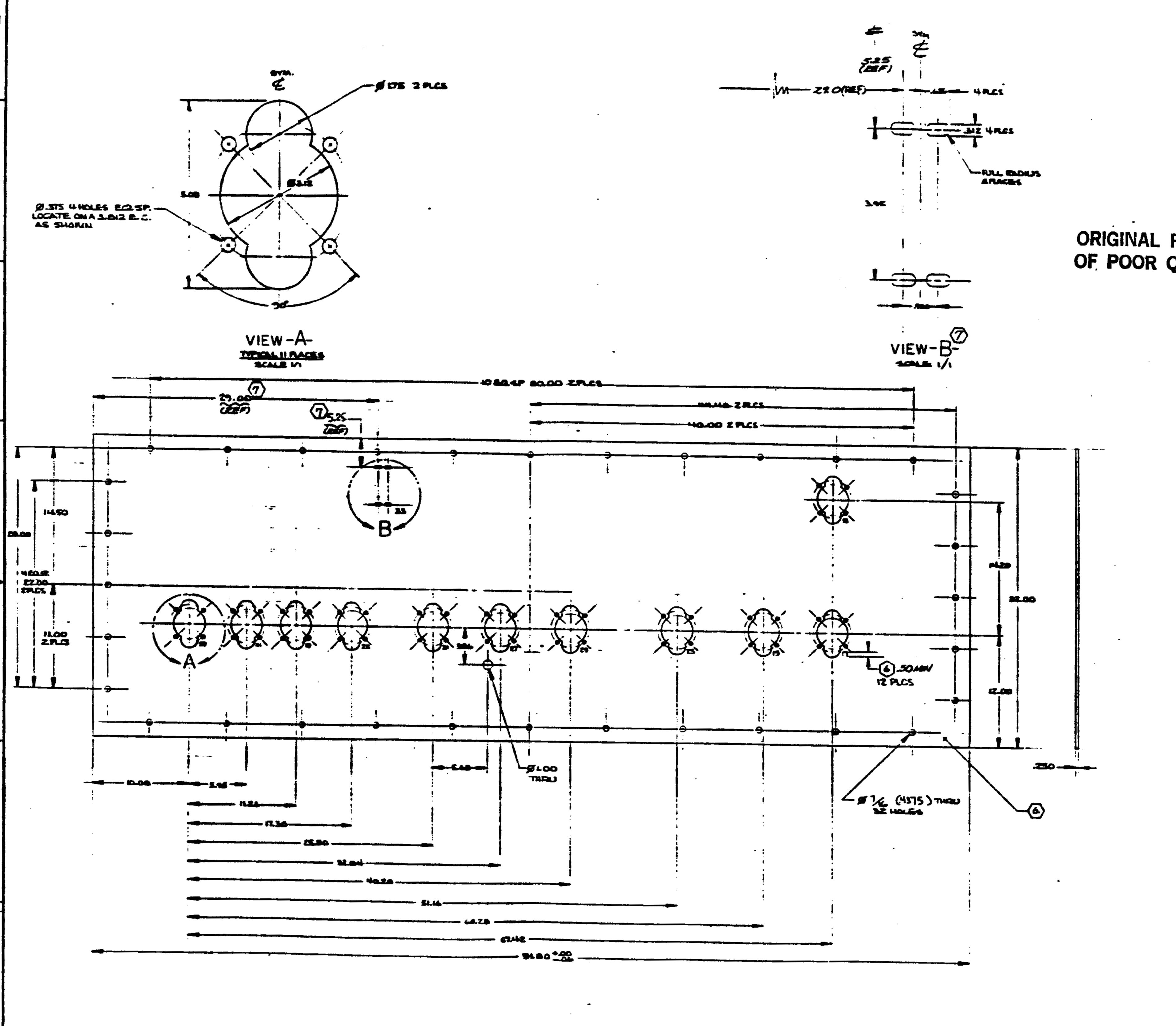

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7. BOLT HOLES TO BE LOCATED ON FINAL ASSEMBLY IN FIELD
6. STENCIL PAINT ALL COMPONENT NUMBERS & A MKR AS SHOWN USING EPOXY COAT PER MIL-C-22750. COLOR: WHITE
5. PAINT PER RA0108-012 USING ALUMINUM CONVERSION COATING PER MIL-C-5541 USING EPOXY COAT PER MIL-C-22750 ALL SURFACES. COLOR: BLACK
4. ALUM PLATE .250X36.0X96.0 6061-T4 OR T6 COND. QQ-A-250/11 AMS 4027
3. CLEAN PER RA0110-34
2. STANDARD DETAILS PER RA0102-007
1. MACHINE PER RA0103-016

PANEL - CONTROL
H_2/O_2

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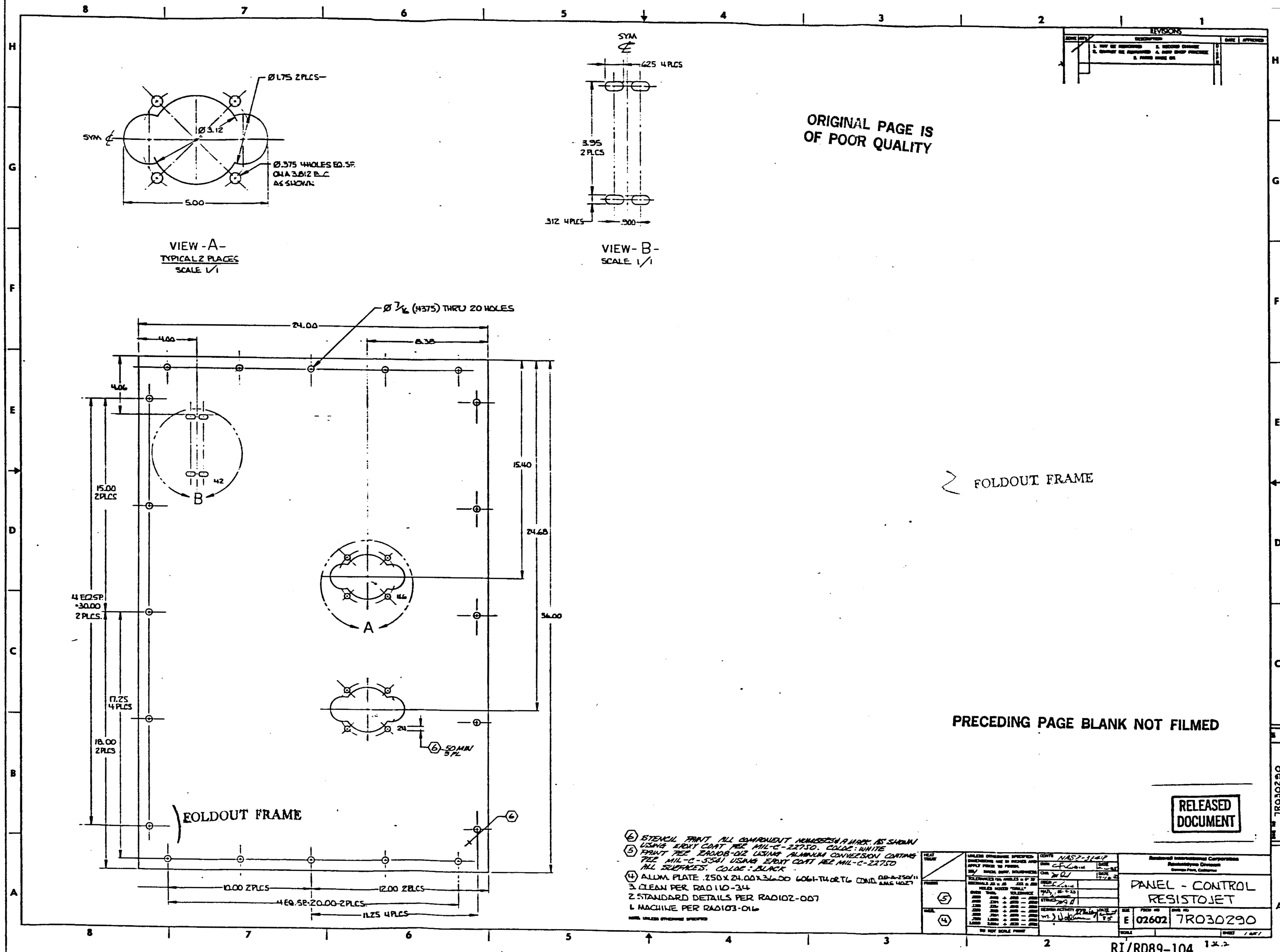

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6. STENCIL PAINT ALL COMPONENT NUMBERS & MARK AS SHOWN USING EPOXY COAT PER MIL-C-22750. COLOR: WHITE
5. PAINT PER ZA0108-012 USING ALUMINUM CONVERSION COATING PER MIL-C-5541 USING EPOXY COAT PER MIL-C-22750 ALL SURFACES. COLOR: BLACK
4. ALUM. PLATE .250 X 24.00 X 36.00 6061-T4 OR T6 COND. QQ-A-250/11 AMS 4027
3. CLEAN PER RA0110-34
2. STANDARD DETAILS PER RA0102-007
1. MACHINE PER RA0103-016

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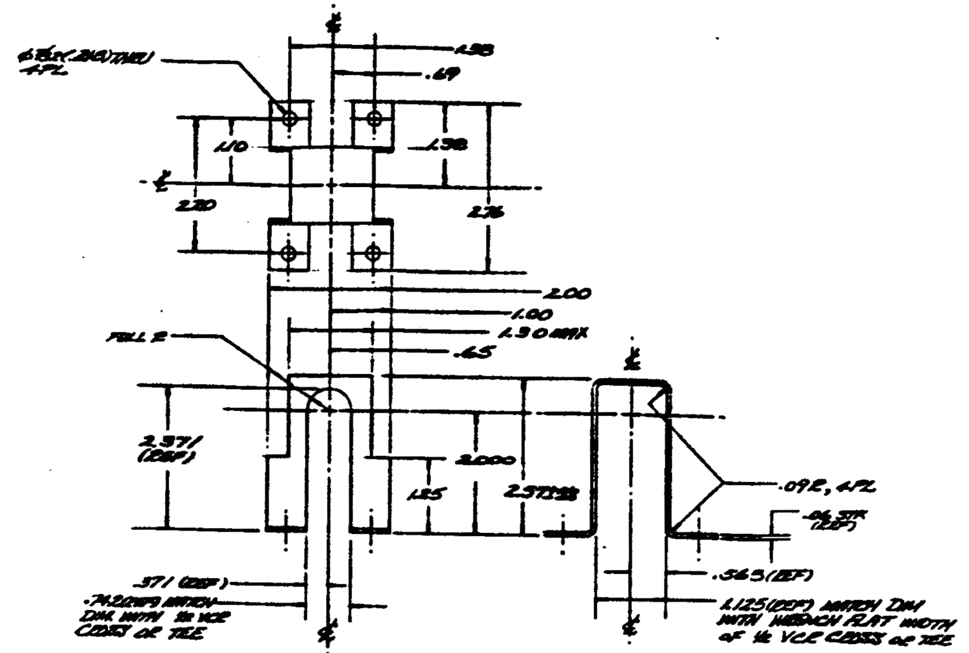
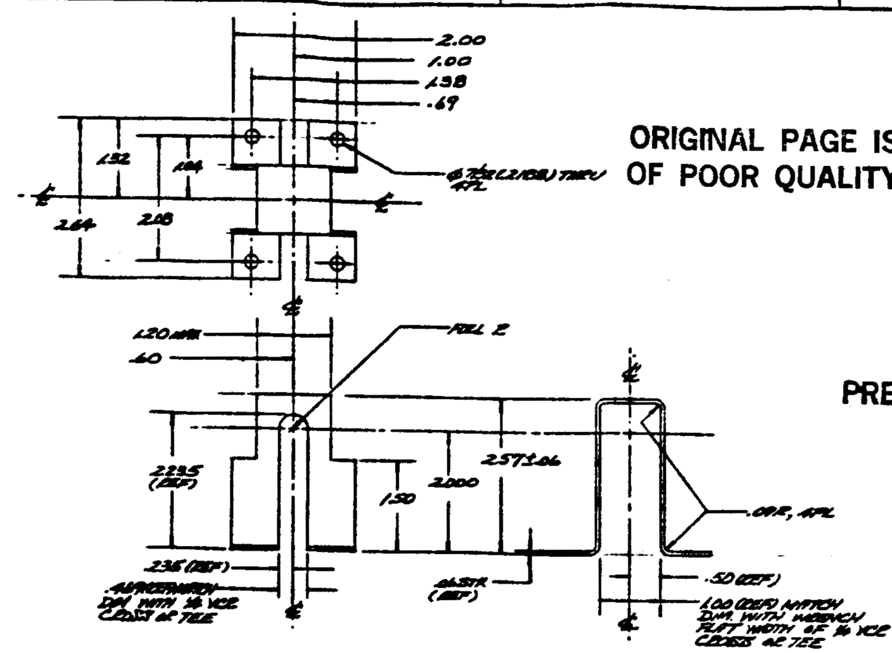


DETAIL A



DETAIL B

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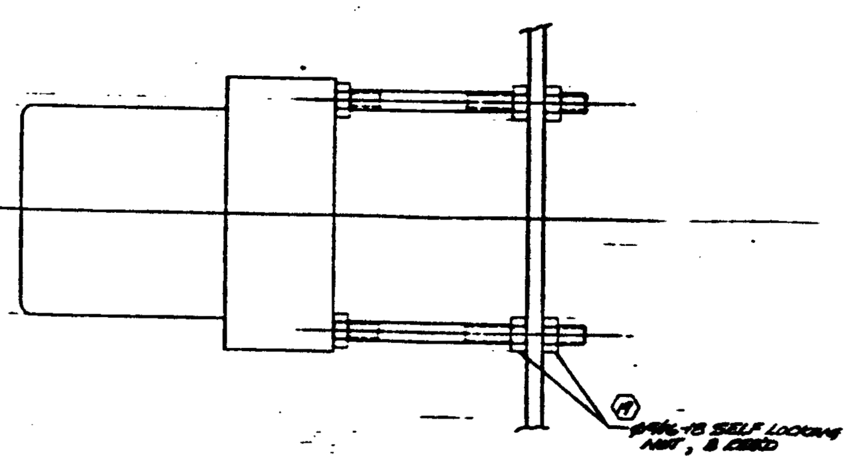

DETAIL C

20. IDENTIFY ALL CONNECTORS AND COMPONENTS WITH METAL TAG IDENTIFICATION PLATE PER 280104-008 AS SPECIFIED ON 7R030294

(17) A1 NUT & BOLT, 2466 TROPIC PARK DRIVE, [illegible] (818) 686-5155

(16) INSTALL TUBE FITTINGS PER 280102-005

(17) ATTACH VALVE PNEUMATIC ACTUATOR TO PANEL WITH 4 BOLTS PER "DETAIL C".

(16) ATTACH FITTING TO PANEL PER "DETAIL B" IF REQ'D

(15) ATTACH FITTING TO PANEL PER "DETAIL A" IF REQ'D

(14) TUBING TO BACK SURFACE OF PANEL USING .25 X .035 WALL 321 CRES TUBING PER MIL-T-8808 & PER MS FLARE TUBES 37° FOR PRESSURE REGULATOR CONTROL SYSTEM, PRESSURE TRANSDUCER AND VENT PER NOTE 2 AND NOTE 3 OF 7R030294.

(13) DRILL BLIND GASKET SHARP EDGE [illegible] DIA

~~(12) FLOW DYNE ENGINEERING, FT. WORTH, TEXAS.~~

11. HELIUM LEAK CHECK AFTER PROOF PRESSURE TEST AT 100 PSI LEAKAGE NOT TO EXCEED 5x10⁻⁶ SCC/SEC.

10. PROOF PRESSURE TEST ASSEMBLY AT [illegible] FOR 5 CYCLES OF 5 SEC. MIN. EACH.

9. PROTECTOR CAPS SHALL BE PLACED AND REMAIN ON ALL VCR FITTING THREADED ENDS UNTIL CONNECTIONS ARE TO BE MADE.

(8) INSTALL VCR GASKETS & RETAINER AT EACH CONNECTION - INSTALLATION AND TORQUE SHALL BE PER CAJON TECH BULLETIN NO. [illegible]

7. INSTALL PNEUMATIC CONTROLS, COMPONENTS AND PRESSURE INSTRUMENTATION ON BACK SURFACE OF PANEL PER 7R030294 FIELD FIT PLUMBING USING .25 X .035 WALL 321 CRES TUBING PER MIL-T-8808 AND PER MS FLARE TUBES 37°.

(6) VACCO INDUSTRIES, SO. EL MONTE, CAL.

(5) CAJON CO., MACEDONIA, OHIO.

(4) NUPRO CO., WILLOUGHBY, OHIO.

~~(3) STENCIL PAINT ALL IDENTIFICATIONS AS SHOWN USING EPOXY PAINT PER MIL-C-22750. COLOR WHITE.~~

~~(2) PAINT PER [illegible] USING ALUMINUM CONVERSION COATING PER MIL-C-5541 [illegible] USING EPOXY COAT PER MIL-C-22750. COLOR BLACK.~~

1 CLEAN PER RL10001.

(23) TORQUE TO 35-40 FT-LB. LUBE THREADS WITH KETTOR PER 280102-002

22. COORDINATE INSTALLATION OF PRESSURE TRANSDUCERS ON 7R030292 FOR CONVENIENCE OF LOCATION.

21. FIELD FIT PLUMBING FOR ALL PRESSURE TRANSDUCERS ISOLATION VALVES, VENT STACK PURGE VALVES AND ORIFICES SPECIFIED ON 7R030294 TO BACK SURFACE OF PANEL.

Note	QTY REQ O_2	QTY REQ H_2	ITEM NO	PART NO	DESCRIPTION	MAT'L SPECIFICATION
(5)	1	1	38	SS-8VCR-6-DF-4	VCR FEMALE FEMALE REDUCING UNION	316 CRES
	5	5	37	7R030299-11	TUBE TO MALE VCR	
	12	12	36	7R030298-11	TUBE TO FEMALE VCR	
(5)	2	2	35	SS-8-VCR-2-BL-UP	VCR BLIND GASKET	316 CRES
	5	5	34	7R030299-1	TUBE TO MALE VCR	
	9	9	33	7R030298-1	TUBE TO FEMALE VCR	
	~~1~~	~~1~~	~~32~~	~~7R032242-1~~	~~THERMOCOUPLE BRIDGE ASSY~~	
	4	4	31	7R032242-11	THERMOCOUPLE BRIDGE ASSY	
	8	8	30	-5	.25 X .035 WALL TUBING	321 CRES/MIL-T-8808
	11	11	29	-3	.50 X .049 WALL TUBING	321 CRES/MIL-T-8808
	1	1	28	7R030289-3	PANEL	
	~~1~~	~~1~~	~~27~~	~~SS-8-VCR-1-4~~	~~VCR MALE CONNECTOR~~	~~316 CRES~~
	~~1~~		~~26~~	~~SS-8-VCR-9~~	~~VCR ELBOW~~	~~316 CRES~~
~~(5)~~	~~1~~	~~1~~	~~25~~	~~SS-4-VCR-1-BL~~	~~VCR BLIND FEMALE NUT~~	~~316 CRES~~
(13)(5)	1	1	24	SS-4-VCR-2-BL-UP	VCR BLIND GASKET	
(5)	7	1	23	SS-4-VCR-CS	VCR CROSS	
(8)(5)	60	60	22	SS-8-VCR-2-UP	VCR GASKET	
(8)(5)	60	60	21	SS-8-VCR-2-GR	VCR GASKET RETAINER	
(8)(5)	31	37	20	SS-4-VCR-2-UP	VCR GASKET	
(8)(5)	31	31	19	SS-4-VCR-2-GR	VCR GASKET RETAINER	
(5)	6	7	18	SS-8-VCR-CS	VCR CROSS	
(5)	8	7	17	SS-8-VCR-T	VCR TEE	
(5)	13	13	16	SS-4-VCR-7-8VCR F	VCR REDUCING ADAPTER	
(5)	3	3	15	SS-4-VCR-T	VCR TEE	
(5)	1	7	14	SS-8-VCR-1-BL	VCR BLIND FEMALE NUT	316 CRES
	1	1	13	7R032246-11	ADAPTER - VCR TO VCR(R)	
	3	3	12	7R032246-1	ADAPTER - VCR TO VCR (R)	
(18)	6	6	11	7R032248-1	ADAPTER - VCR TO AN	
	2	2	10	7R032241-1	ADAPTER - TEMP SENSOR	
	1	1	9	TBD	SONIC ORIFICE ASSY	
	1	—	8	7R032253-11	SONIC ORIFICE ASSY	
	—	1	7	7R032253-1	SONIC ORIFICE ASSY	
(6)	1	1	6	FID10446	VACCO FILTER	
(23)	~~1~~	~~1~~	~~5~~	~~7R032245-11~~	BURST DIAPHRAM ASSY	
(23)	3	3	4	7R032245-1	BURST DIAPHRAM ASSY	
	1	1	3	DT164276	REGULATOR DOME MODEL	
(4)	4	4	2	SS4UK-VSI-4C	NUPRO VALVE	
(4)	7	7	1	SS8UK-V19-4C	NUPRO VALVE	
	-1	-11	—	7R030291	CONTROL ASSEMBLY	

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CONTROL ASSEMBLY
H_2/O_2

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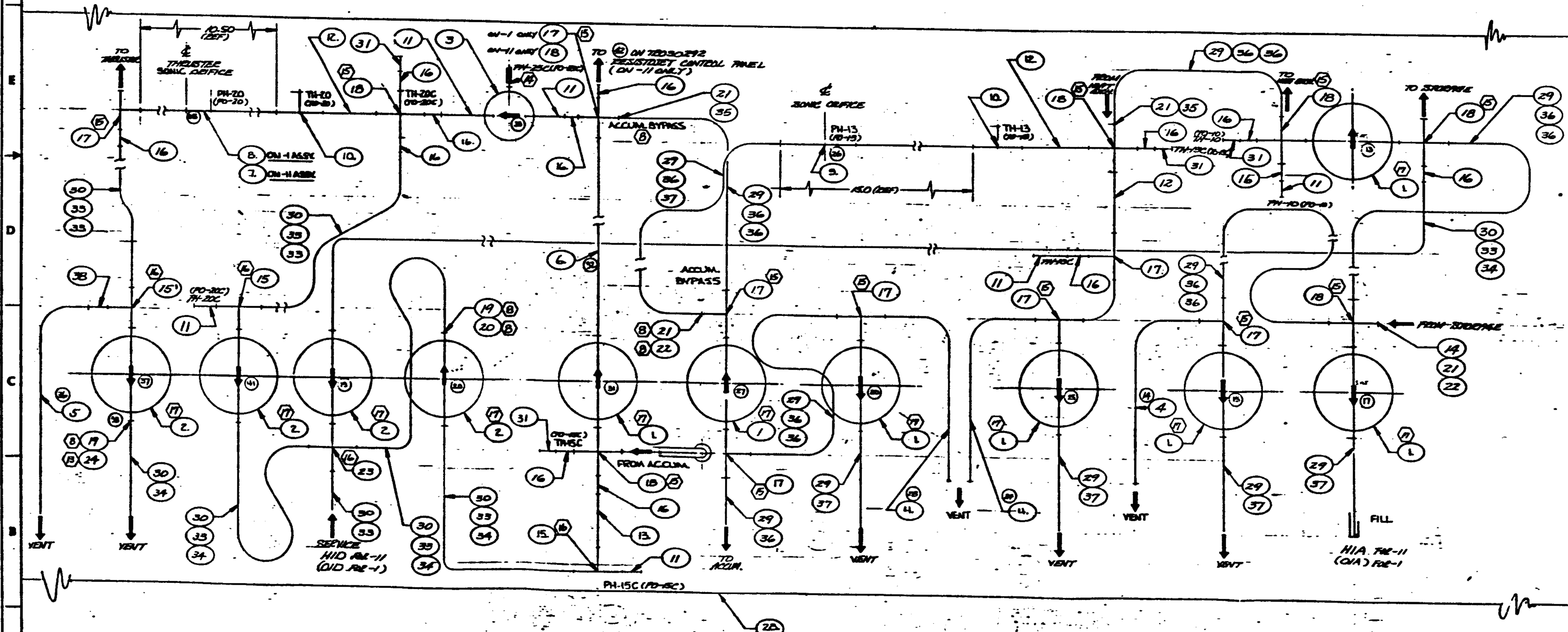

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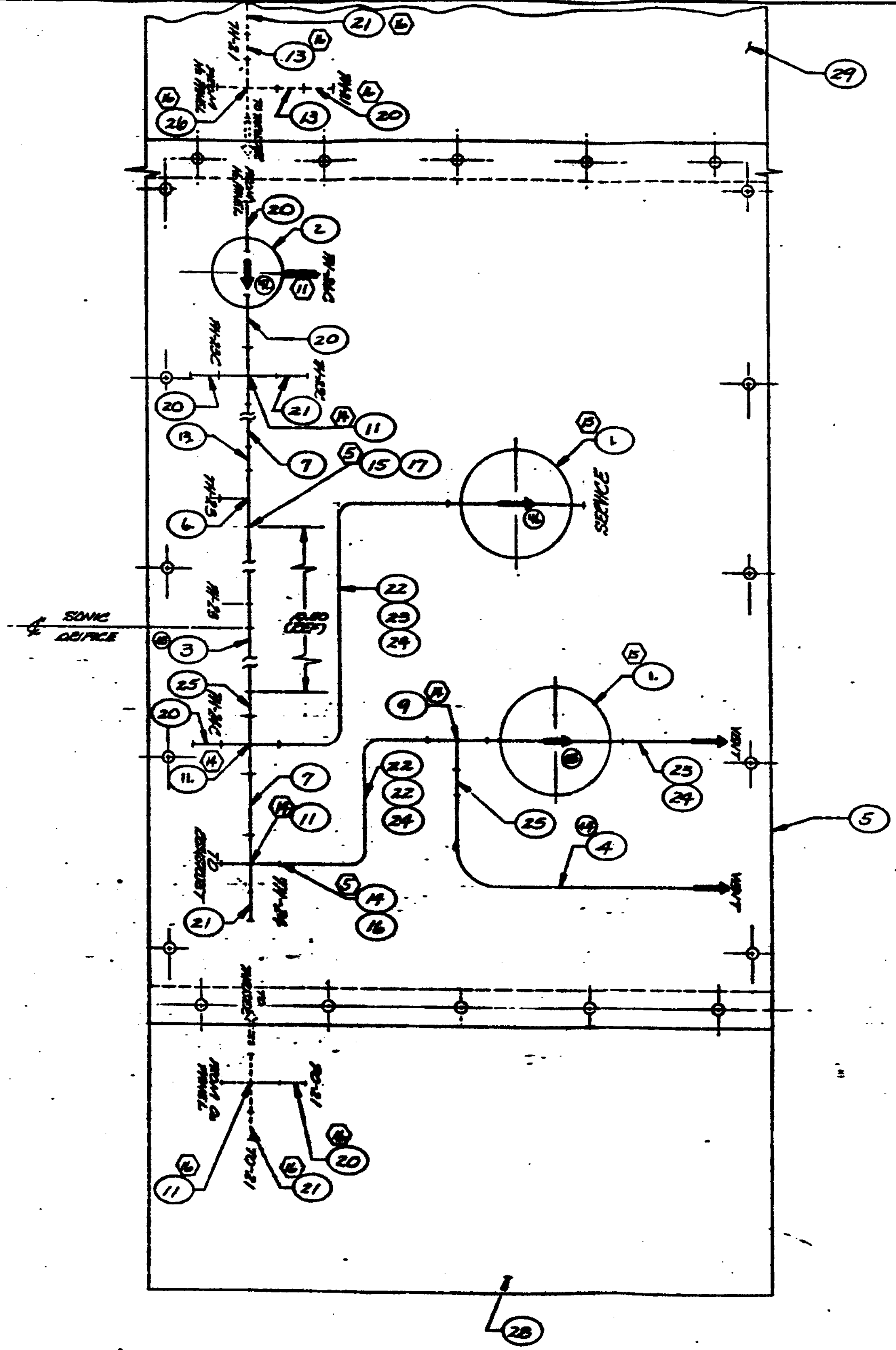

-1 ASSY

18. FIELD FIT PLUMBING FOR ALL PRESSURE TRANSDUCERS, ISOLATION VALVES, VENT STACK PURGE VALVES AND ORIFICES SPECIFIED ON 7R030294 TO BACK SURFACE OF PANEL

17. IDENTIFY ALL CONNECTORS AND COMPONENTS WITH METAL TAG IDENTIFICATION PLATE PER RA0104-008 AS SPECIFIED ON 7R030294

16 MOUNTED ON BACK SIDE OF PANEL.

15 ATTACH VALVE PNEUMATIC ACTUATOR TO PANEL WITH 4 BOLTS PER DETAIL C OF 7R030291

14 ATTACH FITTING TO PANEL PER DETAIL B OF 7R030291 IF REQD

13 INSTALL TUBE FITTINGS PER RA0103-005

~~12 FLOW-DYNE ENGINEERING, FT. WORTH, TEXAS~~

11 PLUMB TO BACK SURFACE OF PANEL USING 1/4 x .028 321 CRES TUBING PER MIL-T-8808 AND PER MS FLARE TUBES 37° FOR PRESSURE REGULATING CONTROL SYSTEM, PRESSURE TRANSDUCER AND VENT PER NOTE 2 AND NOTE 3 OF 7R030294.

10 CAJON CO, MACEDONIA, OHIO

9 NUPRO CO., WILLOUGHBY, OHIO

8. HELIUM LEAK CHECK AFTER PROOF PRESSURE TEST AT 100 PSI LEAKAGE NOT TO EXCEED 5×10^{-6} SCC/SEC.

7. PROOF PRESSURE TEST ASSEMBLY AT 2,500 PSIG FOR 5 CYCLES OF 5 SECONDS MIN. EACH.

6. PROTECTOR CAPS SHALL BE PLACED AND REMAIN ON ALL VCR FITTING BEADED ENDS UNTIL CONNECTIONS ARE TO BE MADE.

5 INSTALL VCR GASKETS & RETAINER AT EACH CONNECTION - INSTALLATION AND TORQUE SHALL BE PER CAJON TECH BULLETIN NO. 2-82

4. INSTALL PNEUMATIC CONTROLS, COMPONENTS AND PRESSURE INSTRUMENTATION ON BACK SURFACE OF PANEL PER 7R030294 FIELD FIT PLUMBING USING 1/4 x .028 321 CRES TUBING PER MIL-T-8808 AND PER MS FLARE TUBES 37°.

~~3 STENCIL PAINT ALL IDENTIFICATIONS AS SHOWN USING EPOXY COAT PER MIL-C-22750 COLOR: WHITE~~

~~2 PAINT PER ... ALUMINUM CONVERSION COATING PER MIL-C-5541 OR MIL-P-... USING EPOXY COAT PER MIL-C-22750 COLOR: BLACK~~

1. CLEAN PER RL00001-...

NOTES: UNLESS OTHERWISE SPECIFIED

28 TORQUE TO 35-40 FT-LB. LUBE THREADS WITH KRYTOX PER RA0112-002

19. COORDINATE INSTALLATION OF PRESSURE TRANSDUCERS ON 7R030292 FOR CONVENIENCE OF LOCATION

Notes	Nº REQ	ITEM Nº	PART NUMBER	DESCRIPTION	MAT'L SPECIFICATION
	1	29	-7	WING PLATE (H_2)	3/16 x 12 x 24 AL PLATE
	1	28	-5	WING PLATE (O_2)	3/16 x 12 x 24 AL PLATE
~~5 10~~	~~2~~	~~27~~	~~SS-4-VCR-7-8VCRF~~	~~VCR REDUCING ADAPTER~~	
5 10	1	26	SS-8-VCR-CS	VCR CROSS (1/2")	
5 10	2	25	SS-8-VCR-6-DF-4	VCR DOUBLE FEMALE REDUCING UNION	
	3	24	-5	1/4 x .028 TUBING	321 CRES/MIL-T-8808
	2	23	7R030299-1	TUBE TO MALE VCR	
	3	22	7R030298-1	TUBE TO FEMALE VCR	
	4	21	7R032242-1	THERMOCOUPLE PROBE ASSY	
15	6	20	7R032243-1	ADAPTER - VCR TO AN	
	~~1~~	~~19~~	~~7R030290~~	~~PANEL~~	
~~5 10~~	~~1~~	~~18~~	~~SS-4-VCR-1-BL~~	~~VCR BLIND FEMALE PLUG~~	~~316 CRES~~
5 10	8	17	SS-8-VCR-2-GR-UP	VCR GASKET RETAINER	
5 10	26	16	SS-4-VCR-2-GR-UP	VCR GASKET RETAINER	
5 10	8	15	SS-8-VCR-2-UP	VCR GASKET	
5 10	26	14	SS-4-VCR-2-UP	VCR GASKET	
5 10	3	13	SS-4-VCR-7-8-VCRF	VCR REDUCING ADAPTER	
				~~VCR~~	
5 10	4	11	SS-4-VCR-CS	VCR CROSS (1/4")	
~~10~~	~~1~~	~~10~~	~~SS-8-VCR-T~~	~~VCR TEE~~	
5 10	1	9	SS-4-VCR-T	VCR TEE	316 CRES
	~~1~~	~~8~~	~~7R032246-1~~	~~ADAPTER~~	
	1	7	7R032246-11	ADAPTER	
	1	6	7R032241-1	ADAPTER - ...	
	1	5	7R030290-1	PANEL	
20	1	4	7R032244-11	BURST DIAPHRAGM ASSY	
	1	3	7R032253-21	SONIC ORIFICE ASSY	
	1	2	DT164276	REGULATOR GROVE MOD 94	
9	2	1	SS4UK-VSI-4C	NUPRO VALVE	
	1	—	7R030292-1	CONTROL ASSEMBLY	

Rockwell International Corporation
Rocketdyne Division

CONTROL PANEL ASSY.
RESISTOJET GROUP

E 02602 7R030292

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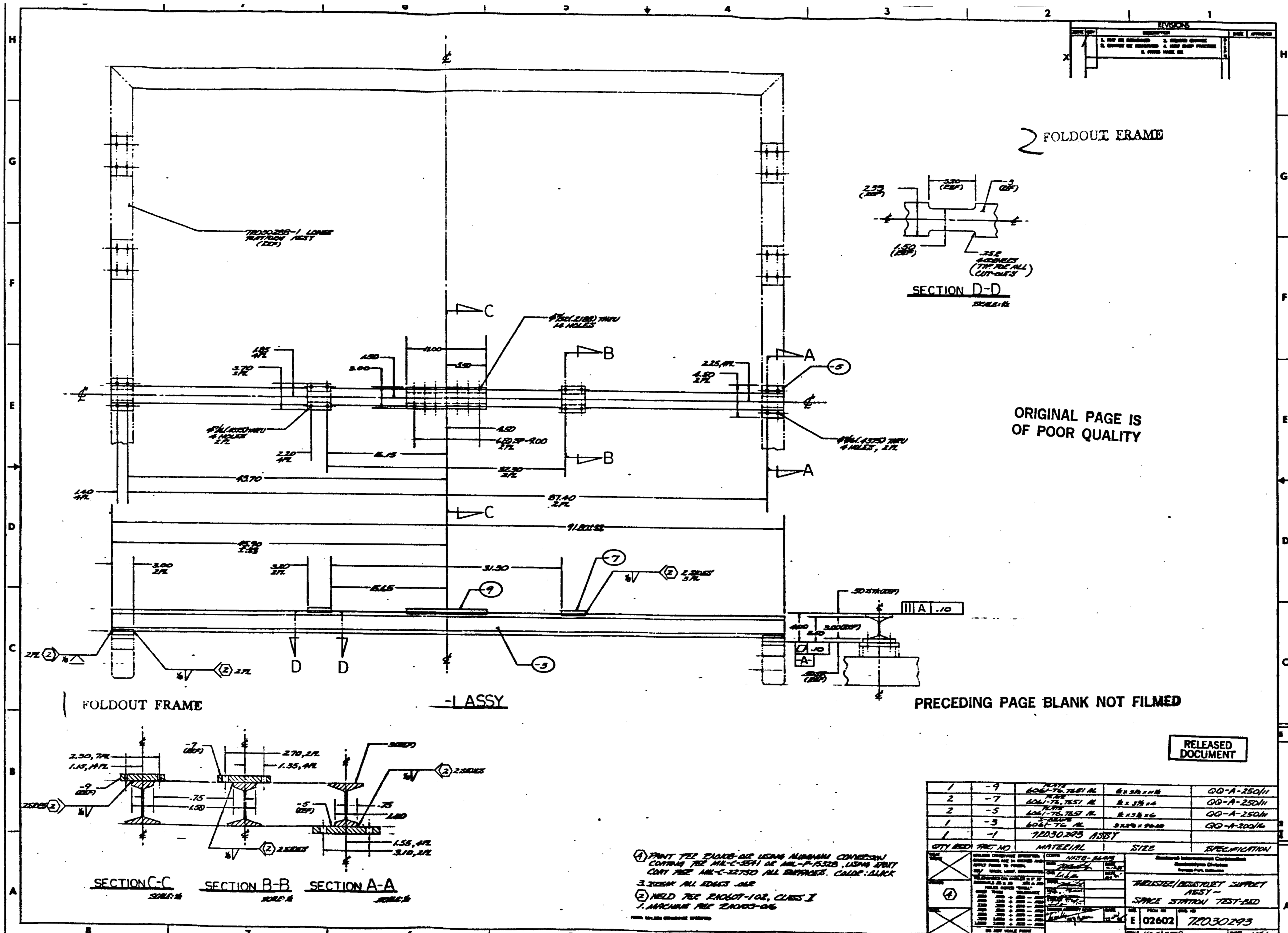
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SECTION D-D
-1 ASSY
SECTION C-C
SECTION B-B
SECTION A-A
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4 PAINT PER ZAO108-012 USING ALUMINUM CONVERSION COATING PER MIL-C-5541 OR MIL-P-15328, USING EPOXY COAT PER MIL-C-22750 ALL SURFACES. COLOR: BLACK
3. BREAK ALL EDGES .02R
2 WELD PER ZAO607-102, CLASS II
1. MACHINE PER ZAO103-016
QQ-A-250/11
QQ-A-250/11
QQ-A-250/11
QQ-A-200/16
7R030293 ASSY
QTY REQD
PART NO
MATERIAL
SIZE
SPECIFICATION
THRUSTER/RESISTOJET SUPPORT ASSY - SPACE STATION TEST-BED
E
02602
7R030293

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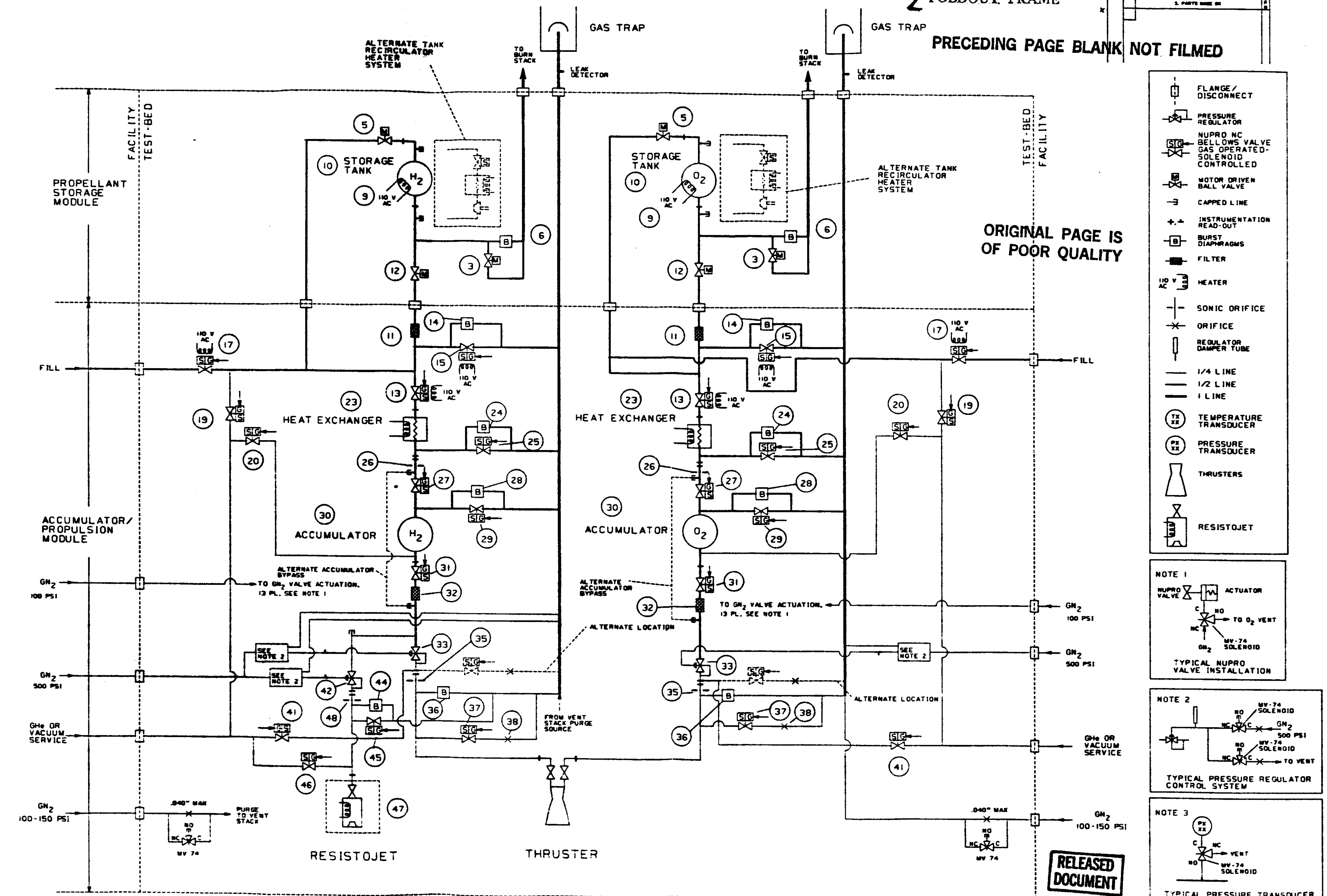

NOTE 4
PROVIDE FILTRATION OF ALL FLUIDS FROM FACILITY TO 10μ NOMINAL, 20μ ABSOLUTE

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Rocketdyne Division

SCHEMATIC, SPACE STATION TEST-BED

E 02602 7R030294

RI/RD89-104
A-27

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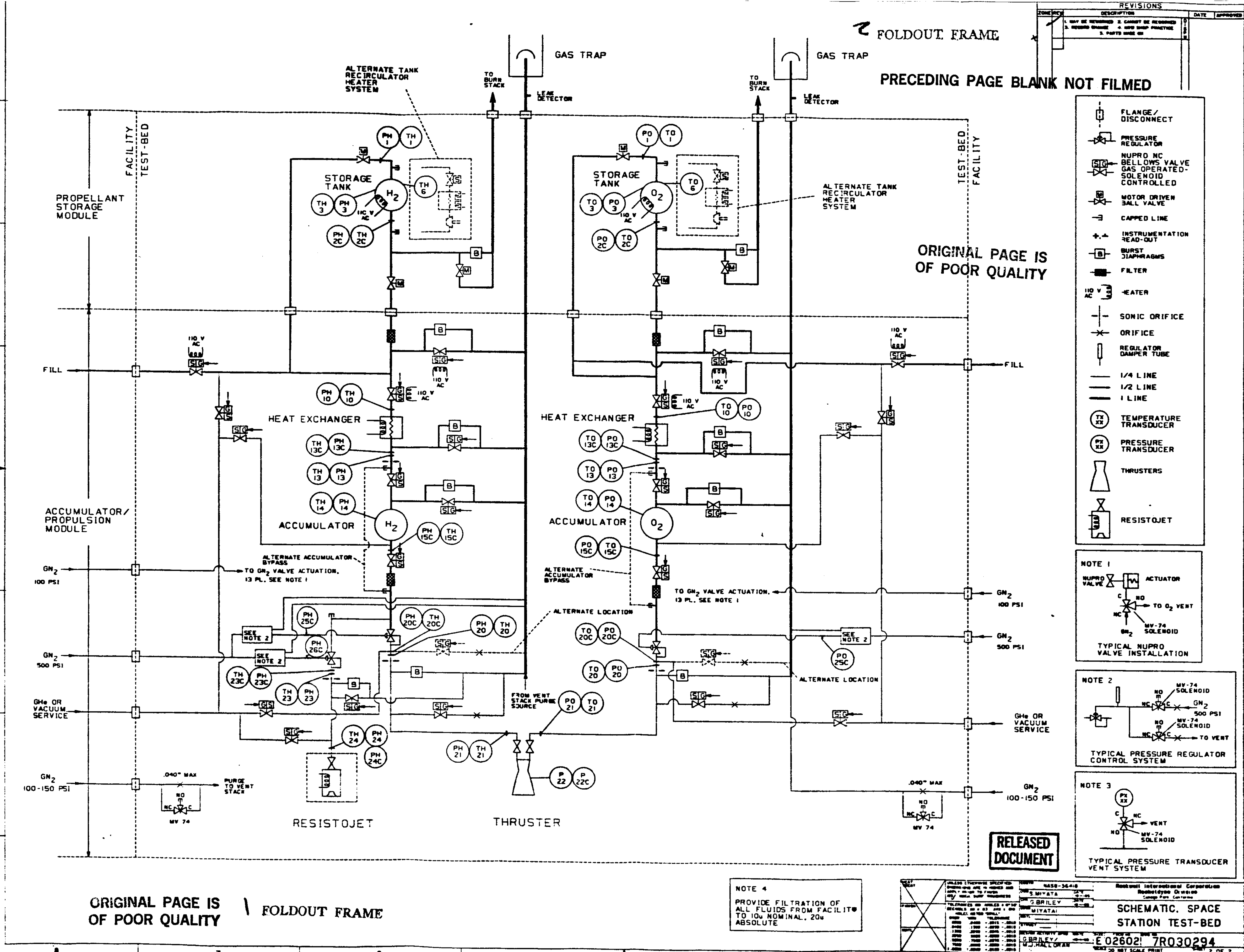
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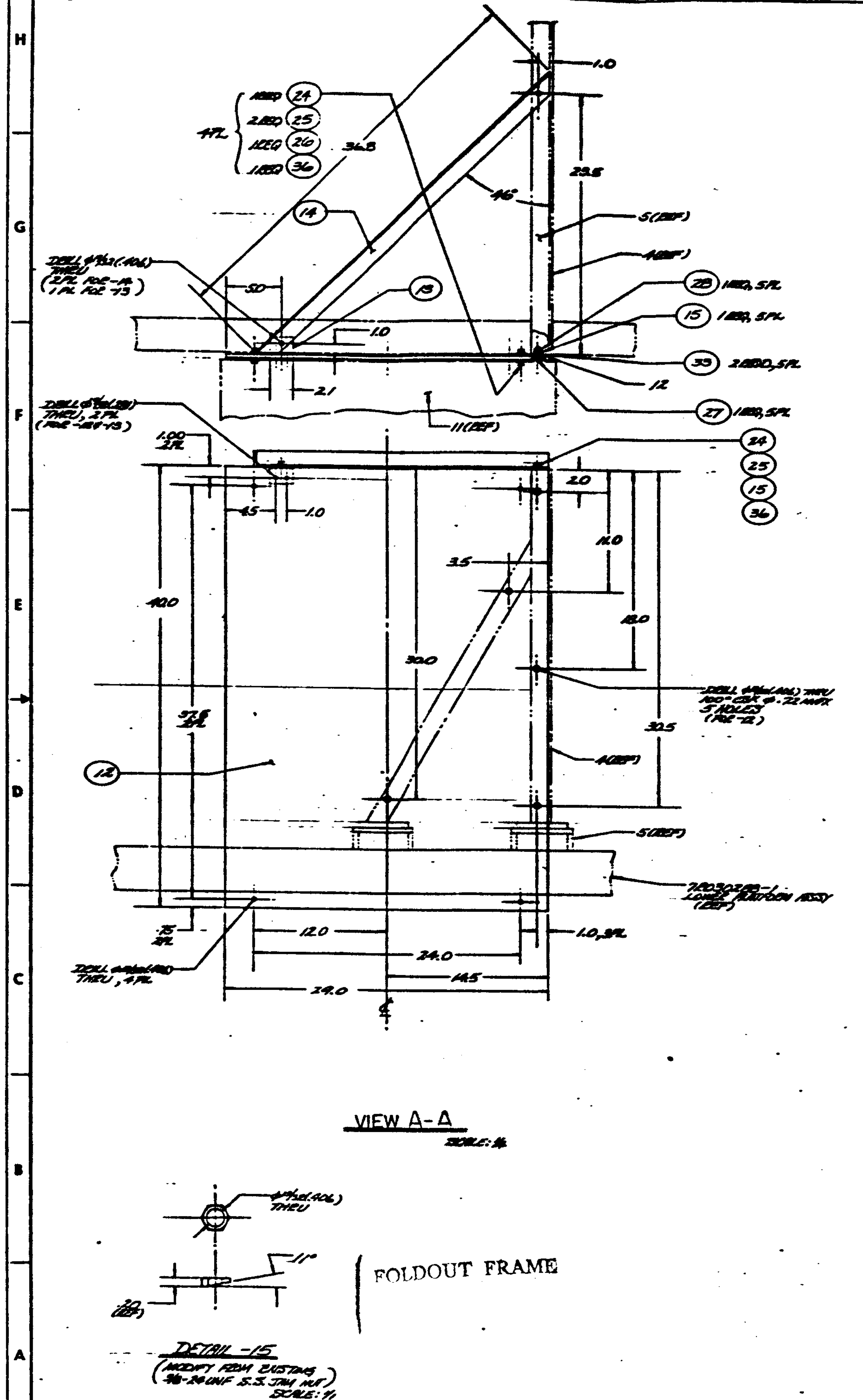
GAS TRAP
TO BURN STACK
LEAK DETECTOR
ALTERNATE TANK RECIRCULATOR HEATER SYSTEM
FACILITY
TEST-BED
PROPELLANT STORAGE MODULE
STORAGE TANK
H_2
O_2
110 V AC
FILL
HEAT EXCHANGER
ACCUMULATOR
ACCUMULATOR/ PROPULSION MODULE
ALTERNATE ACCUMULATOR BYPASS
TO GN_2 VALVE ACTUATION, 13 PL, SEE NOTE 1
GN_2 100 PSI
GN_2 500 PSI
GHe OR VACUUM SERVICE
GN_2 100-150 PSI
SEE NOTE 2
ALTERNATE LOCATION
FROM VENT STACK PURGE SOURCE
.040" MAX
PURGE TO VENT STACK
MV 74
RESISTOJET
THRUSTER
FLANGE/ DISCONNECT
PRESSURE REGULATOR
NUPRO NC BELLOWS VALVE GAS OPERATED-SOLENOID CONTROLLED
MOTOR DRIVEN BALL VALVE
CAPPED LINE
INSTRUMENTATION READ-OUT
BURST DIAPHRAGMS
FILTER
HEATER
SONIC ORIFICE
ORIFICE
REGULATOR DAMPER TUBE
1/4 LINE
1/2 LINE
1 LINE
TEMPERATURE TRANSDUCER
PRESSURE TRANSDUCER
THRUSTERS
RESISTOJET
NOTE 1
NUPRO VALVE
ACTUATOR
TO O_2 VENT
MV-74 SOLENOID
TYPICAL NUPRO VALVE INSTALLATION
NOTE 2
MV-74 SOLENOID
GN_2 500 PSI
TO VENT
TYPICAL PRESSURE REGULATOR CONTROL SYSTEM
NOTE 3
VENT
TYPICAL PRESSURE TRANSDUCER VENT SYSTEM
RELEASED DOCUMENT
NOTE 4
PROVIDE FILTRATION OF ALL FLUIDS FROM FACILITY TO 10μ NOMINAL, 20μ ABSOLUTE
REVISIONS
NAS8-36418
S.MIYATA
G.BRILEY
MIYATAI
G.BRILEY/ M.J.HALLORAN
Rockwell International Corporation
Rocketdyne Division
SCHEMATIC, SPACE STATION TEST-BED
E 02602 7R030294
DO NOT SCALE PRINT
2 OF 2
7R030294



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	QTY REQD	ITEM NO.	PART NO.	DESCRIPTION	MATL-SIZE-SPECIFICATION
	64	41		NUT	3/8-24UNF S.S.
	64	40		BOLT HEX HD	3/8-24UNF X 1 S.S.
	2	39	AN806-J24,K24	PLUG	
(11)	2	38	12100AM24	K-SEAL	
	20	37		BOLT HEX HD	3/8-16UNC X 1¼ S.S.
	26	36		NUT	3/8-16UNC S.S.
(3)	6	35		INSULATOR	
(12)(7)	12	34	EXTT-E-24	THERMOCOUPLES	
	10	33		WASHER FLAT	5/8 S.S.
	2	32		NUT	¼-20UNC S.S.
	2	31		WASHER LOCK	¼ S.S.
	2	30		WASHER FLAT	¼ S.S.
	2	29		BOLT HEX HD	¼-20UNC X 1 S.S.
	5	28		NUT JAM	3/8-24UNF S.S.
	5	27		SCREW CSK HD	3/8-24UNF X 1 S.S.
	5	26		WASHER LOCK	3/8 S.S.
	6	25		WASHER FLAT	3/8 S.S.
	6	24		BOLT HEX HD	3/8-16UNC X 1 S.S.
	12	23		NUT	5/8-18UNF S.S.
	12	22		WASHER FLAT	5/8 S.S.
	6	21		STUD	5/8-18UNF X 4 ½ L S.S.
(8)	40	20		NUT	3/8-16UNC ALLOY STEEL
(8)	40	19		WASHER FLAT	3/8 ALLOY STEEL
(8)	40	18		BOLT HEX HD	3/8-16UNC X 1¼ L ALLOY STEEL
		17			
(9)	1	16	7R032250	INSTRUMENTATION CABLING	
	6	15	-9	SPACER	
	1	14	-7	ANGLE	1½ X 1½ X 36⅞ AL
	1	13	-5	ANGLE	1½ X 1½ X 2⅝ AL
	1	12	-3	PLATE	⅜ X 29 X 40 AL
	1	11	7R032249-1	CONTROL BOX ASSY	
(3)	1	10	45455	ACCUMULATOR ASSY-HYDROGEN	
(5)	1	9	45454	ACCUMULATOR ASSY-OXYGEN	
	1	8	7R030292-1	CONTROL PANEL ASSY-RESISTOJET GROUP	
	1	7	7R030297-1	RESISTOJET COMPONENT PANEL SUPPORT ASSY	
	1	6	7R030293-1	THRUSTER/RESISTOJET SUPPORT ASSY	
	2	5	7R030296-1	COMPONENT PANEL SUPPORT ASSY	
	1	4	7R030291-11	CONTROL ASSY-H_2	
	1	3	7R030291-1	CONTROL ASSY-O_2	
	1	2	7R030283-1	MODULE STRUCTURE ASST	
	1	—	7R030295-1	ACCUMULATOR MODULE ASSY	

(12) OMEGA ENGINEERING, INC, STAMFORD, CONN, 06907
(11) SHELDAHL/HARRISON, BURBANK, CA 91504
(10) 7R032248 INSTRUMENTATION BOX TO BE SHIPPED AS LOOSE EQUIPMENT
(9) INSTALL 59 28 V DC VALVE CONTROL CIRCUIT CABLES, 24 POSITION INDICATOR CIRCUIT CABLES, 7 THERMOCOUPLE CABLES AND 12 PRESSURE TRANSDUCER CABLES PER 7R032251
(8) NICKEL PLATED TO AVOID OUTGASSING

(7) INSTALL THERMOCOUPLES BY WELDING TO EXTERNAL SURFACE OF -9 AND -10 ON A LONGITUDINAL LINE, ONE EACH AT 0°(A), +45°±10°(B), -45°±10°(C), +70°±10°(D) AND -70°±10°(E) AZIMUTH AND ONE AT 0°(F) AZIMUTH ROTATED 90° CIRCUMFERENTIALLY FROM A.
6. PLUMB & INSTALL OXYGEN & HYDROGEN VENT LINES AT LOWER EDGE OF -3 & -4 CONTROL ASSY USING 321 CRES TUBINGS (⌀½ O.D. & ⌀1 O.D. AS REQD). TUBING PER MIL-T-8808 AND PER MS FLARE TUBES 37°. PROVIDE ⌀1" AN CONNECTIONS FOR H/F & H/G FOR -4 (O/F & O/G FOR -3) SPECIFIED ON 7R030294. PROVIDE METAL TAG IDENTIFICATION PLATE PER RA0104-008

(6) CAJON CO. MACEDONIA, OHIO 44056
(4) FIELD FIT VCR FITTINGS AT EACH CONNECTION PER REQD. INSTALLATION AND TORQUE SHALL BE PER CAJON TECH BULLETIN NO. 2-82

(3) CAPITAL WESTWARD, INC. PARAMOUNT, CALIF 90723
2. CLEAN PER RL10001
1. MACHINE PER RA0115-06

NOTES: UNLESS OTHERWISE SPECIFIED

CONTR NAS8-36418

Rockwell International Corporation
Rocketdyne Division
Canoga Park, California

ACCUMULATOR MODULE ASSY
SPACE STATION TEST-BED

E 02602 7R030295

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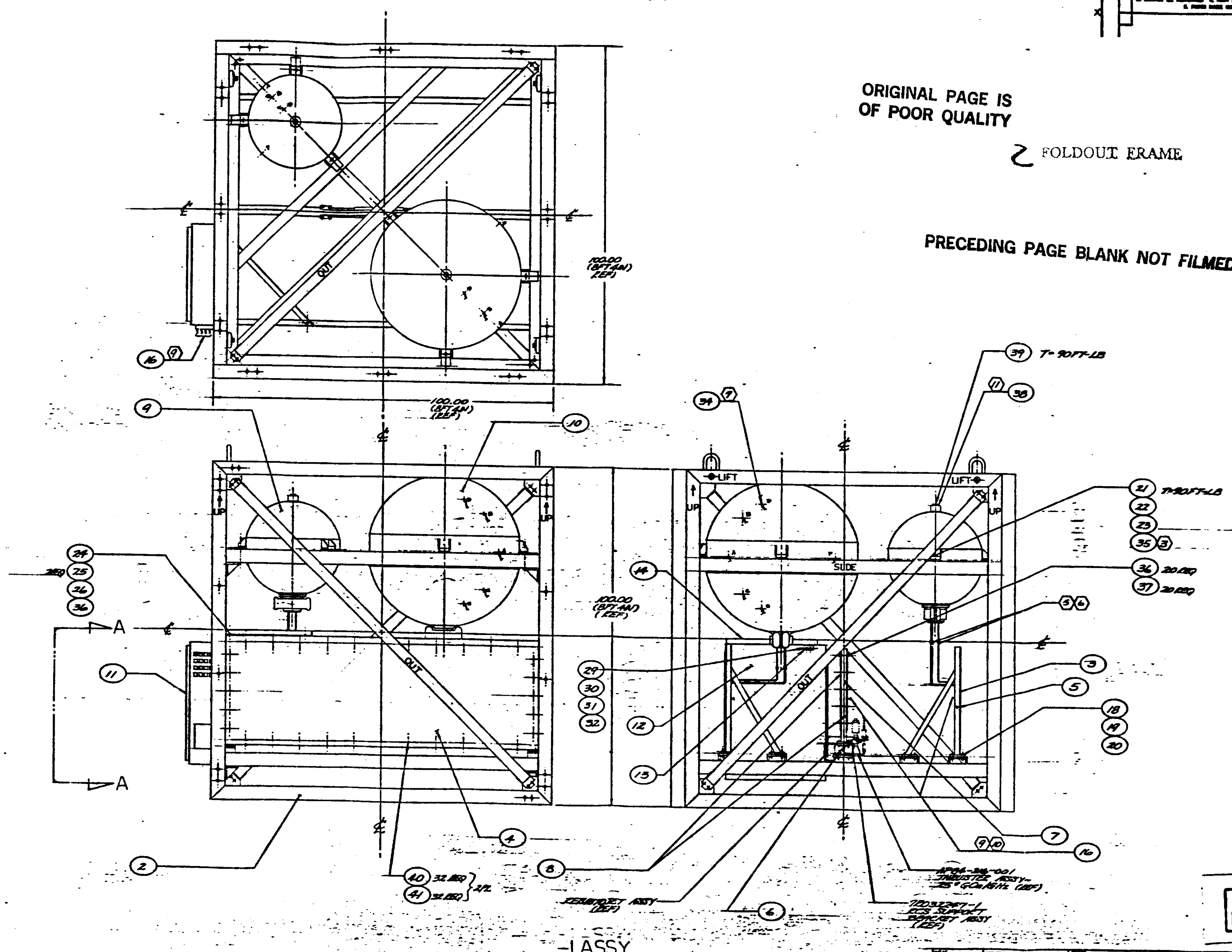

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ACCUMULATOR MODULE ASSY
SPACE STATION TEST-BED

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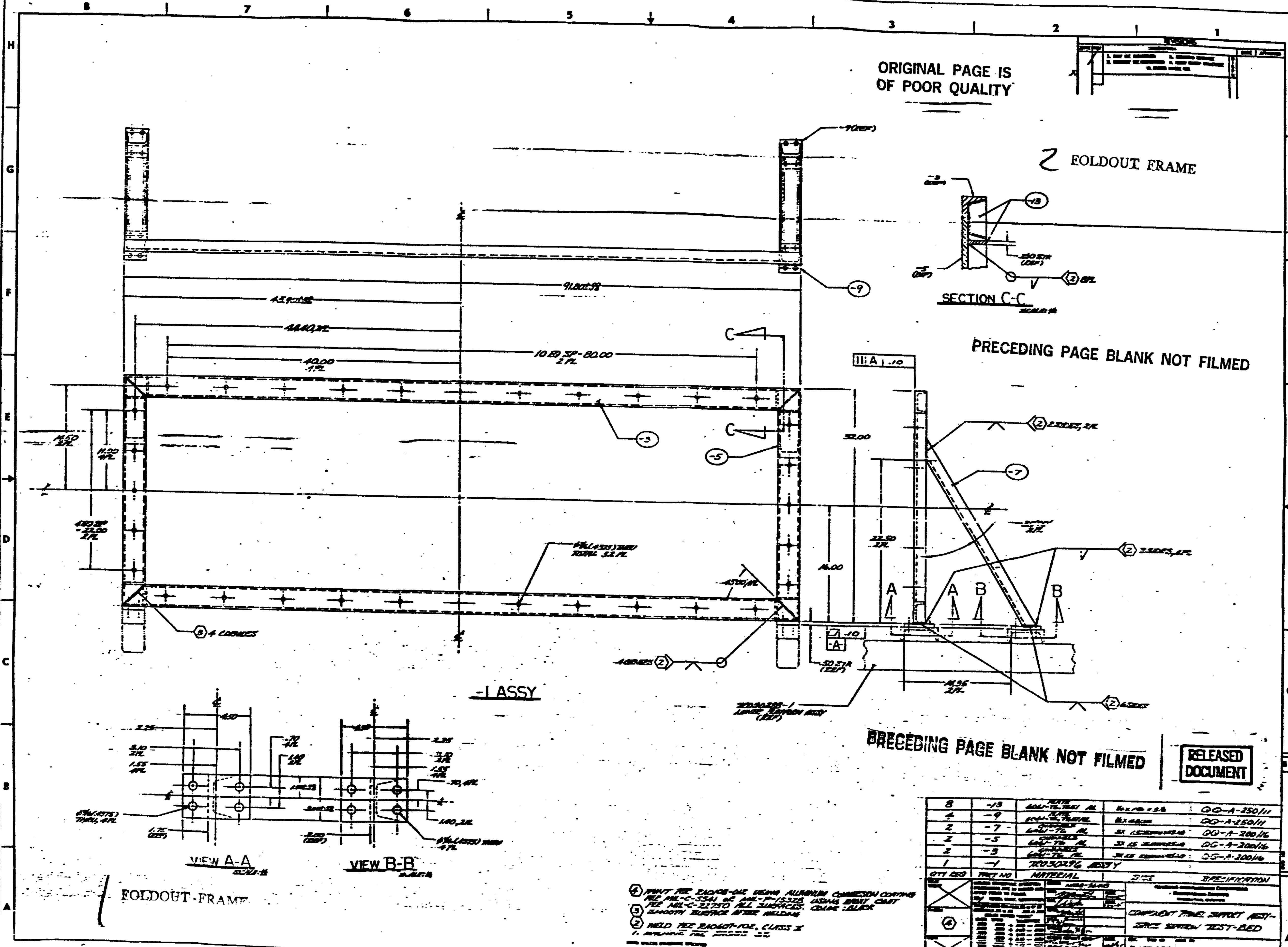

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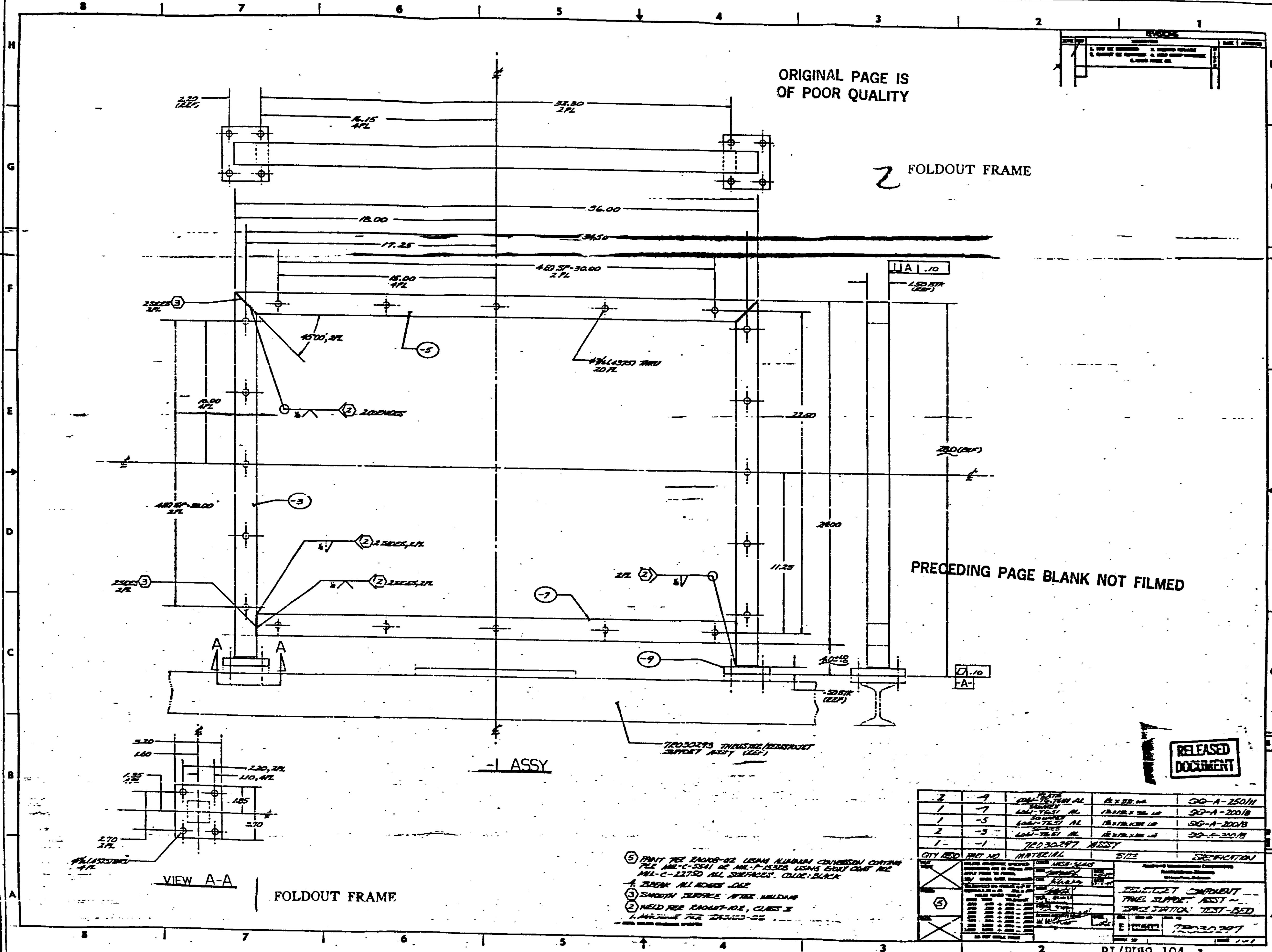

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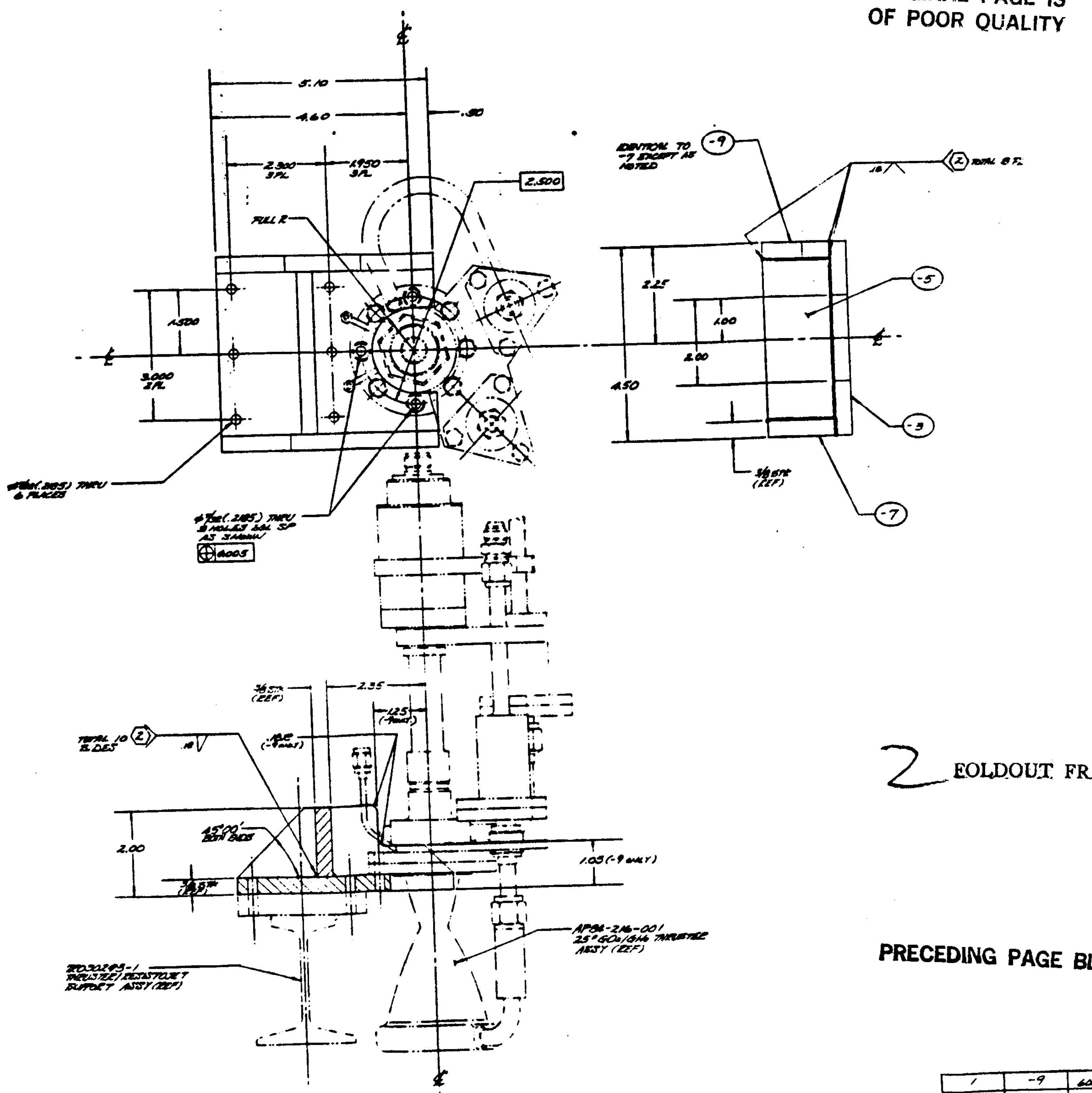

SECTION A-A

-1 ASSY

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3. BREAK ALL EDGES .005R
(2) WELD PER RA0607-102, CLASS I
1. MACHINE PER RA0103-06

QTY REQD	PART NO.	MATERIAL	SIZE	SPECIFICATION
1	-9	PLATE 6061-T6, T651 AL	3/8 x 2 x 5 1/4	QQ-A-250/11
1	-7		3/8 x 2 x 5 1/2	
1	-5		3/8 x 2 x 4 1/2	
1	-3	PLATE 6061-T6, T651 AL	3/8 x 4.50 x 5 1/2	QQ-A-250/11

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Canoga Park, California

RCS SUPPORT BRACKET
ASSY –
SPACE STATION TEST-BED

E 02602 7R032247

ZONE	REV	REVISIONS DESCRIPTION	DATE	APPROVED
		1. MAY BE REWORKED 2. CANNOT BE REWORKED 3. RECORD CHANGE 4. NOW SHOP PRACTICE 5. PARTS MADE OK		

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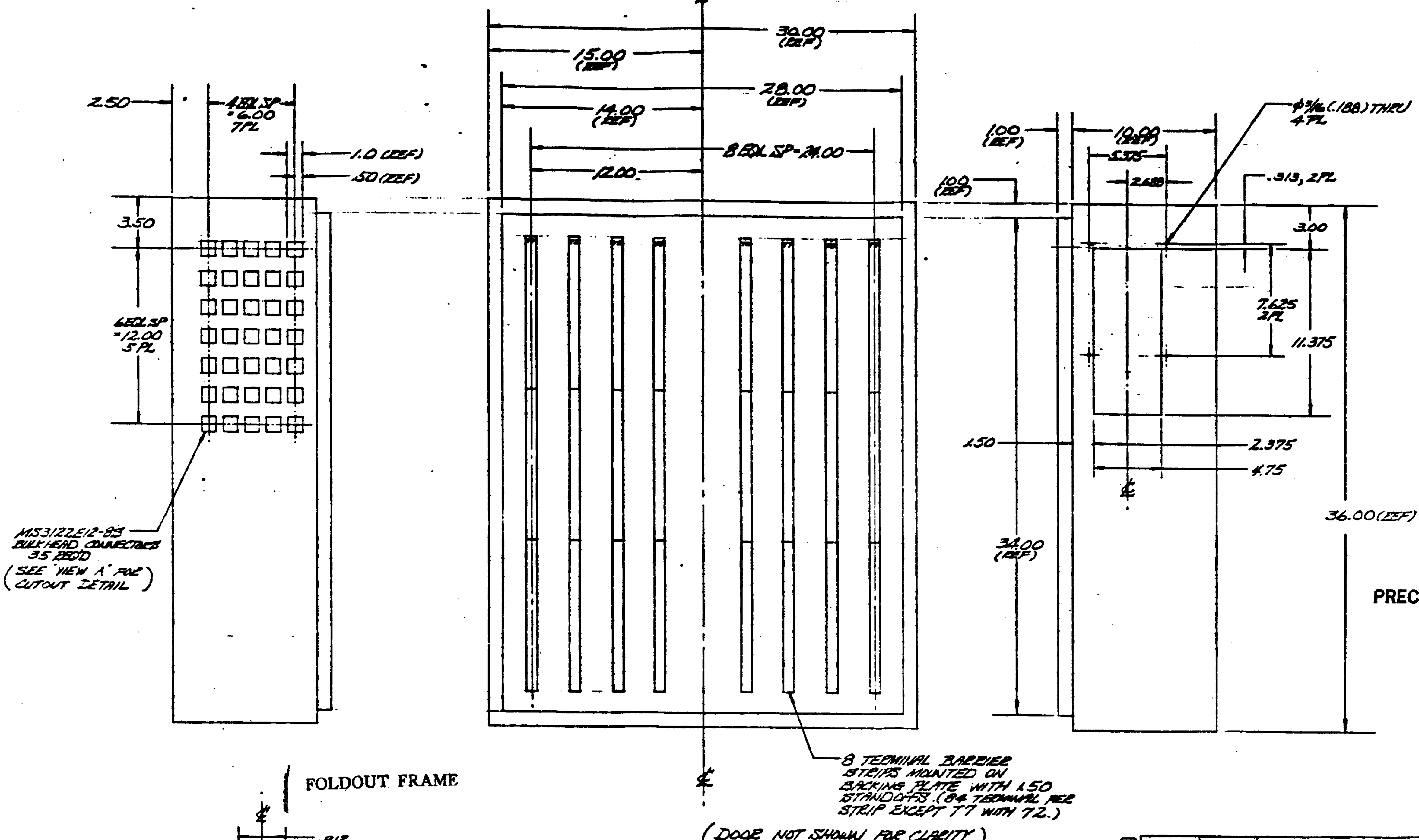

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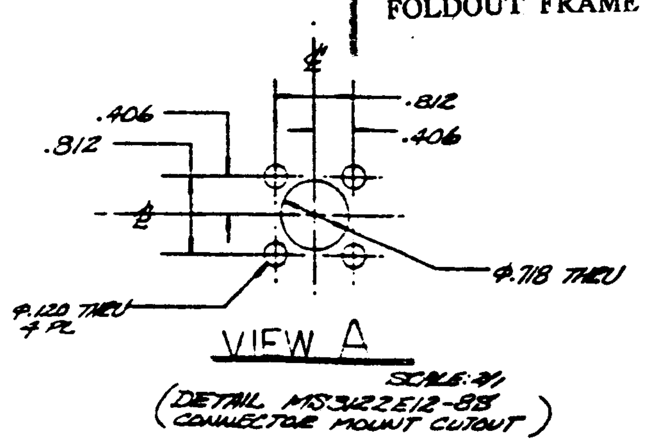

(4) PAINT PER RA0108-012 USING PRIMER PER MIL-P-23377 & MIL-P-52192 USING EPOXY COAT PER MIL-C-22750 ALL SURFACES EXCEPT HOLES. APPLY PRIMER WITHIN 4 HOURS AFTER GRIT BLASTING TO PROTECT FROM RUSTING. COLOR: BLACK

3. CLEANING PROCEDURE AS FOLLOWS:
   1. STEAM CLEAN
   2. CLEAN ALL SURFACES BY GRIT BLASTING TO REMOVE ALL RUST & SCALE
   3. BLOW DOWN ALL SURFACES WITH DRY AIR. VISUALLY INSPECT TO ASSURE ALL SURFACES ARE FREE OF GREASE, OIL AND WAXES PRIOR TO PRIMING

(2) MODIFY EXISTING HOFFMAN ELECTRICAL BOX

1. MACHINE PER RA0103-016

QTY REQD	ITEM NO	PART NO	DESCRIPTION	MAT'L-SIZE-SPEC
(2) 1	—	7R032248-1	INSTRUMENTATION BOX ASSY	

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH. 125/ MACH. SURF. ROUGHNESS. TOLERANCES ON: ANGLES ± 0° 30' DECIMALS .XX ± .03 .XXX ± .010. HOLES NOTED "DRILL" TOLERANCE

DO NOT SCALE PRINT

HEAT TREAT: X
FINISH: (4)
MAT'L: (2)

CONTR NAS8-36418
DWN [signature] DATE 10-4-85
CHK [signature] DATE
DSGN K. CLARK
MAT'L —
STRUCT —
DESIGN ACTIVITY APVD [signature]

Rockwell International Corporation
Rocketdyne Division
Canoga Park, California

INSTRUMENTATION BOX ASSY - SPACE STATION TEST-BED

SIZE D | FSCM NO 02602 | DWG NO 7R032248

SCALE 4 | SHEET 1 OF 1

ZONE	REV	REVISIONS DESCRIPTION	DATE	APPROVED
		1. MAY BE REWORKED 2. CANNOT BE REWORKED 3. RECORD CHANGE 4. NOW SHOP PRACTICE 5. PARTS MADE OK		

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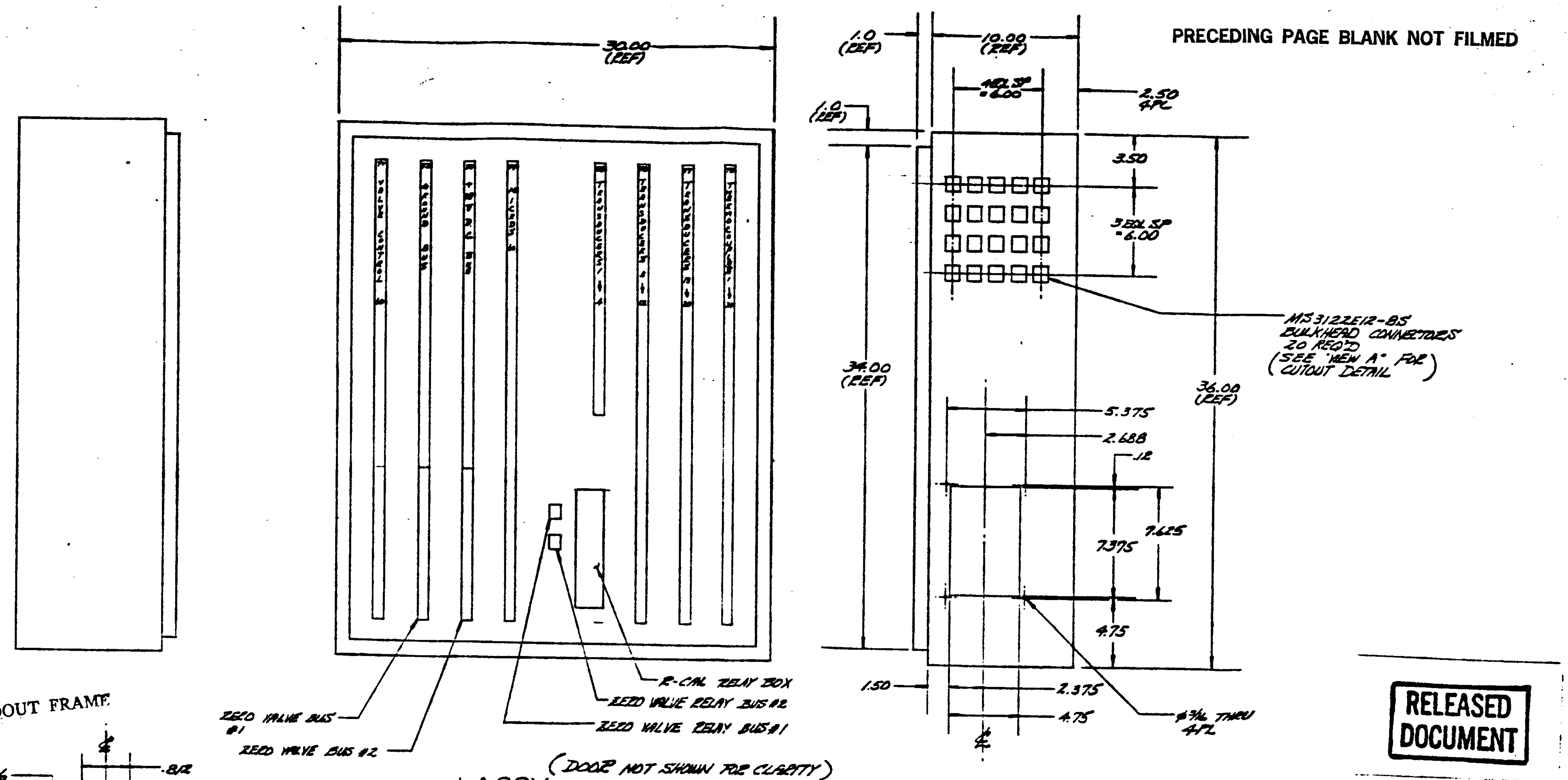

-1 ASSY (DOOR NOT SHOWN FOR CLARITY)

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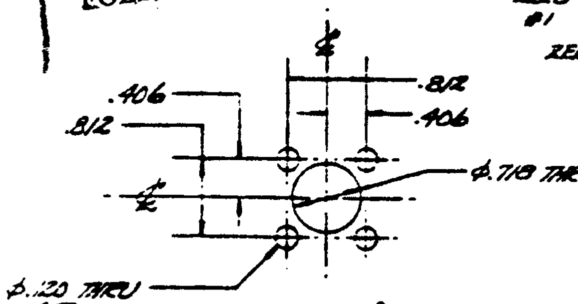

VIEW A SCALE: 2/1 (DETAIL MS3122E12-8S CONNECTOR MOUNT CUTOUT)

4. PAINT PER RA0108-012 USING PRIMER PER MIL-P-23377 OR MIL-P-52192 USING EPOXY COAT PER MIL-C-22750 ALL SURFACES EXCEPT HOLES. APPLY PRIMER WITHIN 4 HOURS AFTER GRIT BLASTING TO PROTECT FROM RUSTING. COLOR: BLACK
3. CLEANING PROCEDURE AS FOLLOW:
   1. STEAM CLEAN
   2. CLEAN ALL SURFACES BY GRIT BLASTING TO REMOVE ALL RUST & SCALE
   3. BLOW DOWN ALL SURFACES WITH DRY AIR VISUALLY INSPECT TO ASSURE ALL SURFACES ARE FREE OF GREASE, OIL AND WAXES PRIOR TO PRIMING
2. MODIFY EXISTING HOFFMAN ELECTRICAL BOX
1. MACHINE PER RA0103-016

QTY REQD	ITEM NO.	PART NO.	DESCRIPTION	MATL - SIZE - SPEC
1	-	7R032249-1	CONTROL BOX ASSY	

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH. 125/ MACH. SURF. ROUGHNESS. TOLERANCES ON: ANGLES ± 0° 30' DECIMALS .XX ± .03 .XXX ± .010. HOLES NOTED "DRILL" DO NOT SCALE PRINT

HEAT TREAT — FINISH (4) — MATL (2)

CONTR NAS8-36418 — DWN — CHK — DSGN K. CLARK — MATL — STRUCT — DESIGN ACTIVITY APPD

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Canoga Park, California

CONTROLS BOX ASSY~ SPACE STATION TEST-BED

SIZE D FSCM NO 02602 DWG NO 7R032249 SCALE 1/8 SHEET 1 OF 1

RI/RD89-104
A-43

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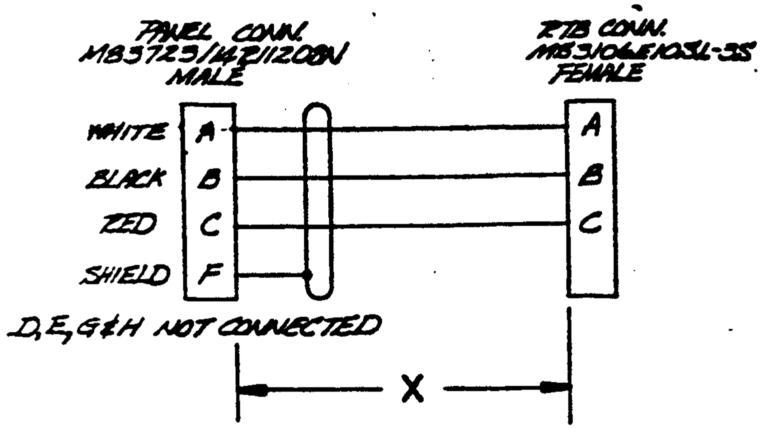
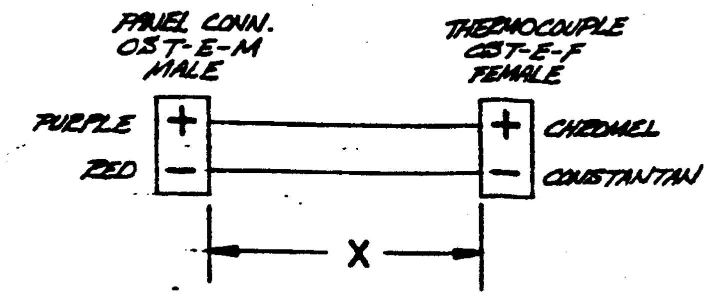


QTY	X (FT)
5	50
2	60

RTB



QTY	X (FT)
31	50
4	60
7	35

THERMOCOUPLE

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ZONE	REV	REVISIONS DESCRIPTION	DATE	APPROVED
		1. MAY BE REWORKED 3. RECORD CHANGE 2. CANNOT BE REWORKED 4. NOW SHOP PRACTICE 5. PARTS MADE OK		

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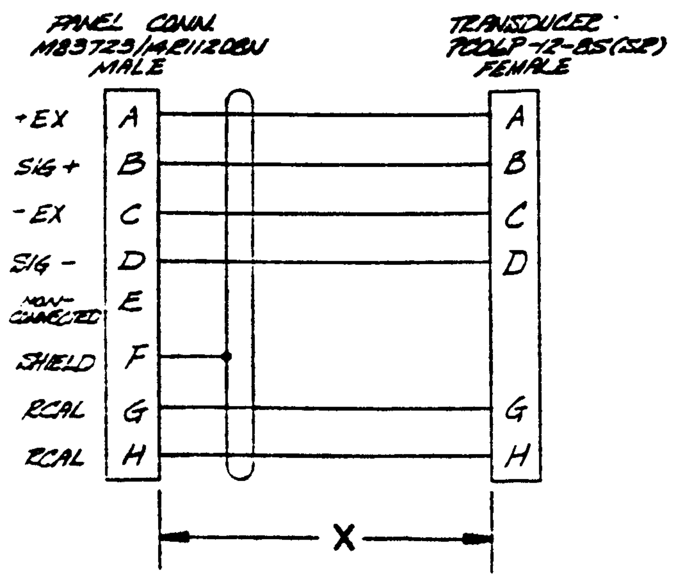
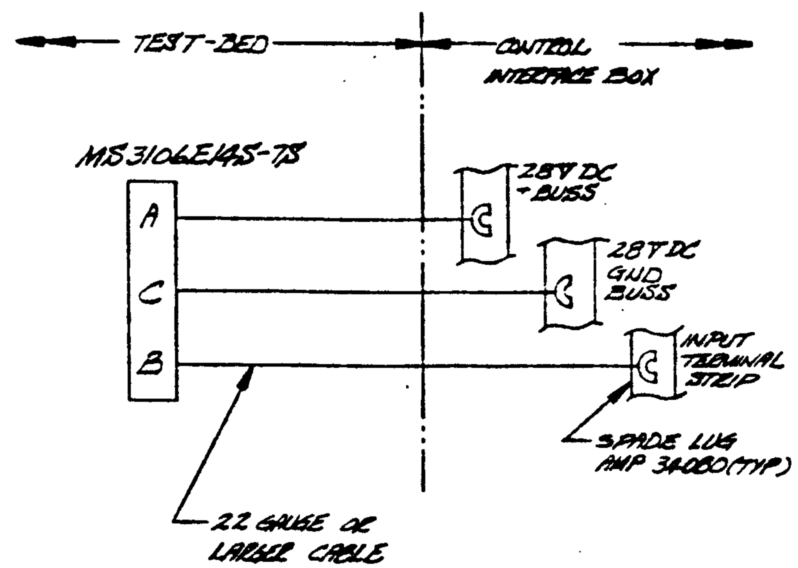


QTY	X (FT)
15	50
12	35
4	60

1 FOLDOUT FRAME

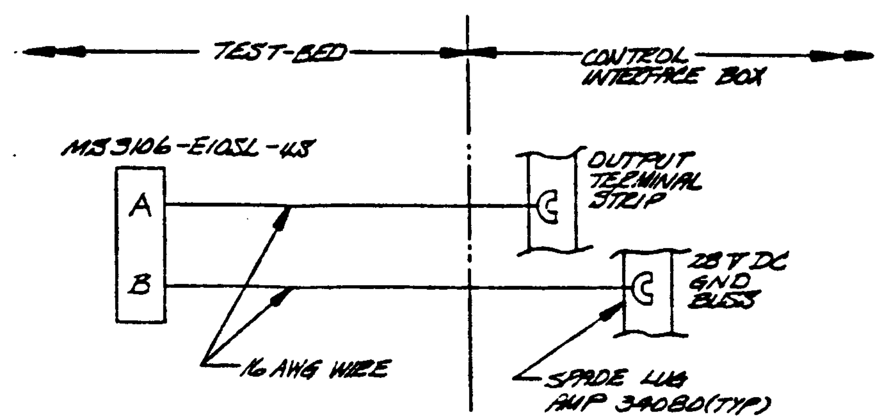
PRESSURE TRANSDUCER



POSITION INDICATOR CIRCUIT - TYPICAL

(LENGTHS FIELD FIT)

NOTE: UNLESS OTHERWISE SPECIFIED



28V DC VALVE CONTROL CIRCUIT - TYPICAL

(LENGTHS FIELD FIT TO VALVES)

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH. 125/ MACH. SURF. ROUGHNESS. TOLERANCES ON: ANGLES ± 0° 30' DECIMALS .XX ± .03 .XXX ± .010 HOLES NOTED "DRILL" DO NOT SCALE PRINT

CONTR NAS8-36418

DSGN K CLARK

Rockwell International Corporation
Rocketdyne Division
Canoga Park, California

INSTRUMENTATION CABLING SPACE STATION TEST-BED

SIZE D | FSCM NO 02602 | DWG NO 7R032250

SCALE RI/RD89-104 SHEET 1 OF 1

VALVE NUMBER	LOCATION	VALVE CONNECTOR PIN	FROM POSITION INDICATOR CONNECTOR PIN	TO CONTROL INTERFACE BOX TERMINAL
H19	H_2 FILL SERVICE ISOLATION	A B	A B C	T1-15 T2-15 T3-15 T4-15 T2-15
H17	H_2 FILL	A B	A B C	T1-16 T2-16 T3-16 T4-16 T2-16
H13	H_2 HEAT EXCHANGER IN	A B	A B C	T1-17 T2-17 T3-17 T4-17 T2-17
H15	H_2 FILL VENT	A B	A B C	T1-18 T2-18 T3-18 T4-18 T2-18
0-41	O_2 SERVICE ISOLATION	A B	A B C	T1-19 T2-19 T3-19 T4-19 T2-19
0-37	O_2 RUNLINE VENT	A B	A B C	T1-20 T2-20 T3-20 T4-20 T2-20
0-33-P	O_2 REG PRESSURIZE	A B		T1-40,T4-40 T2-40
0-33-V	O_2 REG VENT	A B		T1-41,T4-41 T2-41
	O_2 VENT STACK PURGE	A B		T1-42,T4-42 T2-42
0-31	O_2 ACCUMULATOR OUTLET	A B	A B C	T1-24 T2-24 T3-24 T4-24 T2-24
0-29	O_2 ACCUMULATOR VENT	A B	A B C	T1-25 T2-25 T3-25 T4-25 T2-25
0-27	O_2 ACCUMULATOR INLET	A B	A B C	T1-26 T2-26 T3-26 T4-26 T2-26
0-25	O_2 HEAT EXCHANGER VENT	A B	A B C	T1-27 T2-27 T3-27 T4-27 T2-27

VALVE NUMBER	LOCATION	VALVE CONNECTOR PIN	FROM POSITION INDICATOR CONNECTOR PIN	TO CONTROL INTERFACE BOX TERMINAL
H46	RESISTOJET SERVICE ISOLATION	A B	A B C	T1-1 T2-1 T3-1 T4-1 T2-1
H45	RESISTOJET LINE VENT	A B	A B C	T1-2 T2-2 T3-2 T4-2 T2-2
H41	H_2 SERVICE ISOLATION	A B	A B C	T1-3 T2-3 T3-3 T4-3 T2-3
H37	H_2 RUNLINE VENT	A B	A B C	T1-4 T2-4 T3-4 T4-4 T2-4
H42-P	RESISTOJET REG PRESSURE	A B		T1-35,T4-35 T2-35
H42-V	RESISTOJET REG VENT	A B		T1-36,T4-36 T2-36
H33-P	H_2 REG PRESSURIZE	A B		T1-37,T4-37 T2-37
H33-V	H_2 REG VENT	A B		T1-38,T4-38 T2-38
	H_2 VENT STACK PURGE	A B		T1-39,T4-39 T2-39
H31	H_2 ACCUMULATOR OUTLET	A B	A B C	T1-10 T2-10 T3-10 T4-10 T2-10
H29	H_2 ACCUMULATOR VENT	A B	A B C	T1-11 T2-11 T3-11 T4-11 T2-11
H27	H_2 ACCUMULATOR INLET	A B	A B C	T1-12 T2-12 T3-12 T4-12 T2-12
H25	H_2 HEAT EXCHANGER VENT	A B	A B C	T1-13 T2-13 T3-13 T4-13 T2-13
H20	H_2 ACCUMULATOR SERVICE ISOLATION	A B	A B C	T1-14 T2-14 T3-14 T4-14 T2-14

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NOTE: UNLESS OTHERWISE SPECIFIED

INSTRUMENTATION/ CONTROL ASSY SPACE STATION

E 02602 7RC32251

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VALVE NUMBER	LOCATION	VALVE CONNECTOR PIN	POSITION INDICATOR CONNECTOR PIN	CONTROL INTERFACE BOX TERMINAL
0-20	O_2 ACCUMULATOR SERVICE ISOLATION	A B	A B C	T1-28 T2-28 T3-28 T4-28 T2-28
0-19	O_2 FILL SERVICE ISOLATION	A B	A B C	T1-29 T2-29 T3-29 T4-29 T2-29
0-17	O_2 FILL	A B	A B C	T1-30 T2-30 T3-30 T4-30 T2-30
0-13	O_2 HEAT EXCHANGER IN	A B	A B C	T1-31 T2-31 T3-31 T4-31 T2-31
0-15	O_2 FILL VENT	A B	A B C	T1-32 T2-32 T3-32 T4-32 T2-32
	H_2 PROP VALVE	A B		T1-33,T4-33 T2-33
	O_2 PROP VALVE	A B		T1-34,T4-34 T2-34

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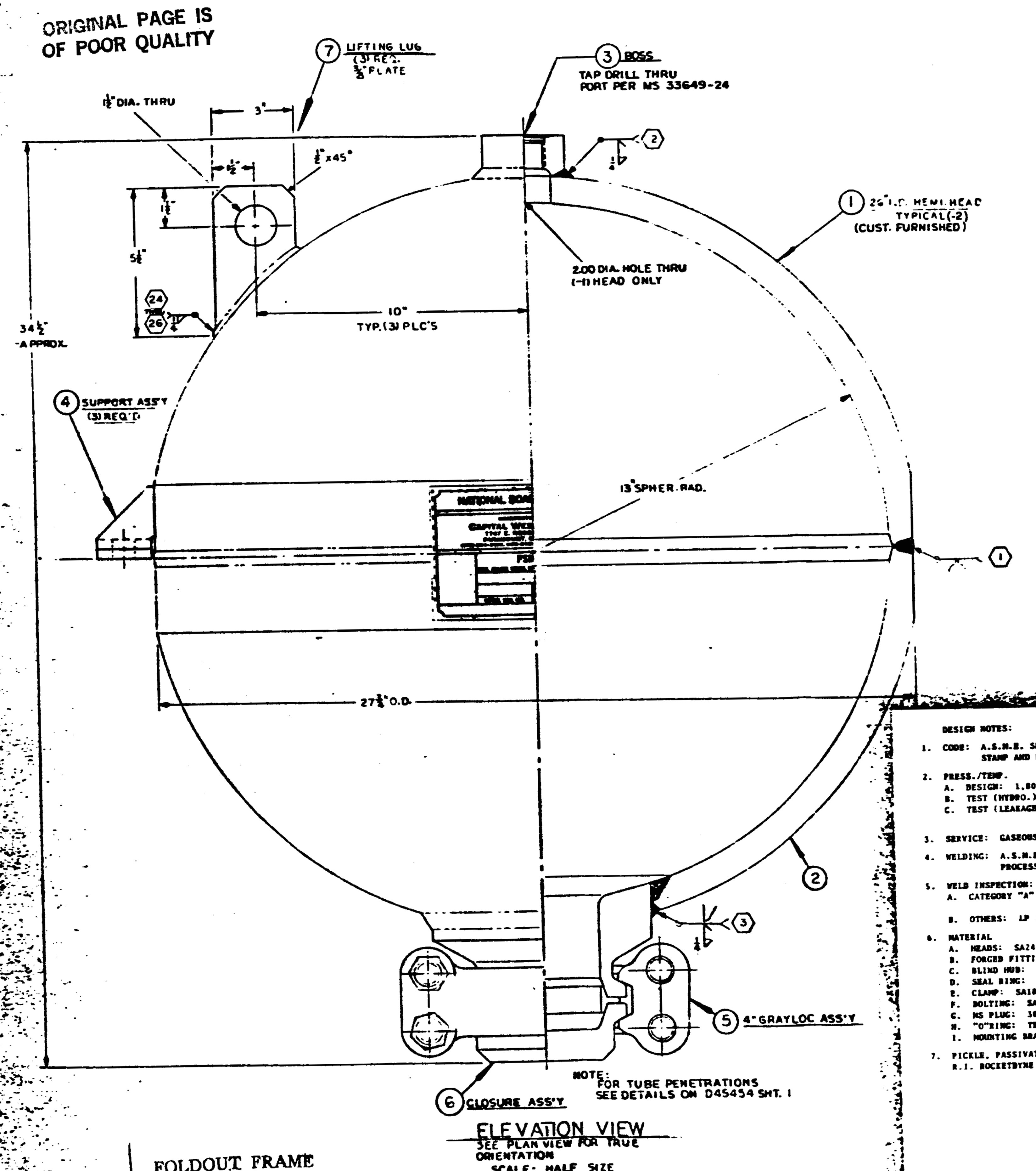
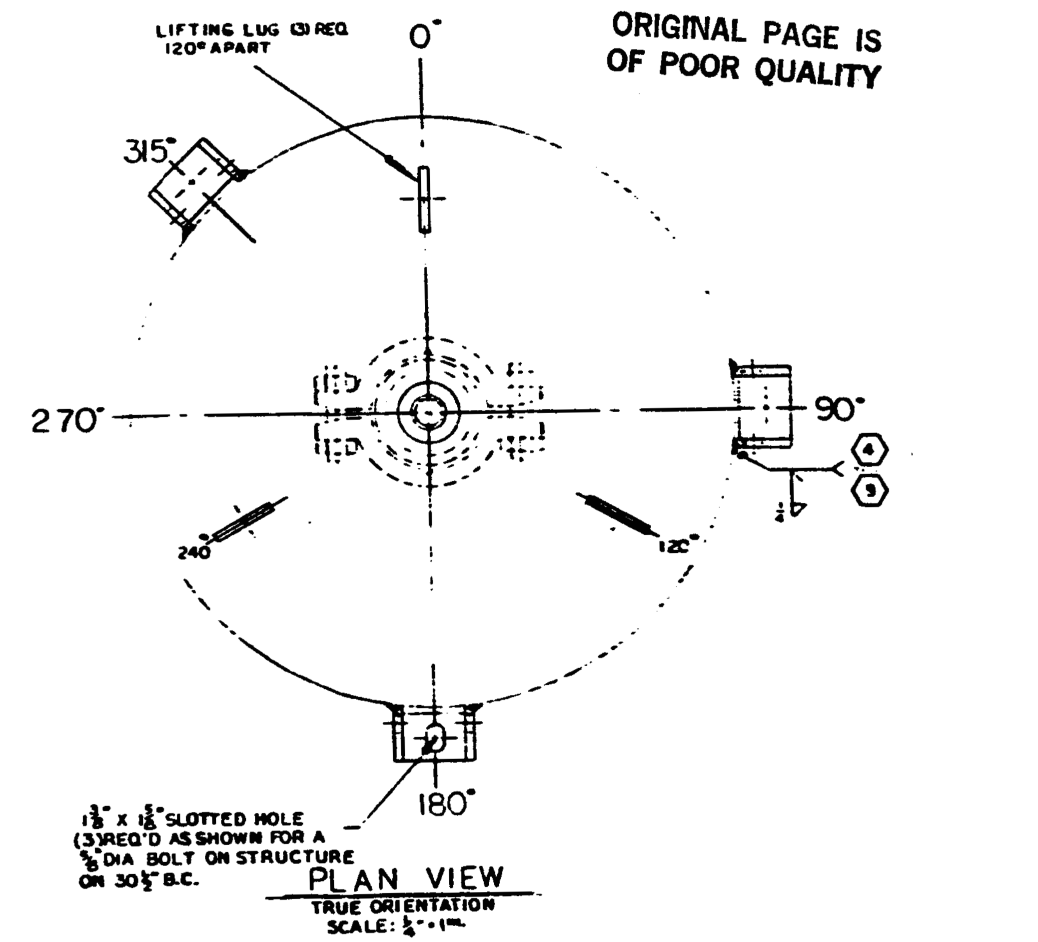


ELEVATION VIEW
SEE PLAN VIEW FOR TRUE ORIENTATION
SCALE: HALF SIZE



PLAN VIEW
TRUE ORIENTATION
SCALE: 1/4" = 1"

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C-3

DESIGN NOTES:

1. CODE: A.S.M.E. SECT. VIII, DIV. 1 LATEST ADDENDA
   STAMP AND DATA SHEET IS REQUIRED
2. PRESS./TEMP.
   A. DESIGN: 1,800 P.S.I.G. @ -200° F to +150° F
   B. TEST (HYDRO.): 2,700 P.S.I.G. @ AMB. TEMP.
   C. TEST (LEAKAGE): LESS THAN 1 X 10^{-5} scc/Sec. HELIUM @ 1,800 P.S.I.G. & AMB. TEMP.
3. SERVICE: GASEOUS OXYGEN. CORR. ALLOW.: NONE
4. WELDING: A.S.M.E. CODE SECT. IX LATEST ADDENDA
   PROCESSES: G.T.A.W., S.M.A.W. & S.A.W.
5. WELD INSPECTION:
   A. CATEGORY "A" WELD: RT 100% PER. A.S.M.E. CODE SECT. VIII, DIV. 1, PARA. UW-51
   B. OTHERS: LP 100% PER. A.S.M.E. CODE SECT. V, ART. 6
6. MATERIAL
   A. HEADS: SA240-304L
   B. FORGED FITTINGS: SA182F304L
   C. BLIND HUB: SA182F316
   D. SEAL RING: TEFLON COATED 17-4 PH
   E. CLAMP: SA182F304
   F. BOLTING: SA193 B8 STUDS/SA194-8 NUTS
   G. MS PLUG: 304 S.S.
   H. "O"RING: TEFLON
   I. MOUNTING BRACKETS: 304L S.S.
7. PICKLE, PASSIVATE & CLEAN PER. THE REQUIREMENTS OF R.I. ROCKETDYNE DIV. SPECIFICATIONS & P.O.

NATIONAL BOARD
CAPITAL WESTWARD, INC.
U W RT-1
1800 PSIG @ -200/+150 °F
45454
3216 | 06907 | 1985

LTR	REVISIONS	DATE
A	Rev. for Fabrication	10-14-85
2	Rev. Per Cust. Approval	7-26-85
1	Rev. Per Cust. Review	7-19-85

TITLE: ACCUMULATOR OXYGEN (TYPE I VESSEL)

CAPITAL WESTWARD, INC.

CW06907-1

DRAWN: RUSS 7-11-85

PO NO R 56-AAA-054591-92

CUSTOMER: ROCKETDYNE

DWG. NO. 45454 SIZE D REV. A

SCALE AS NOTED SHT 1 of 1

RI/RD89-104

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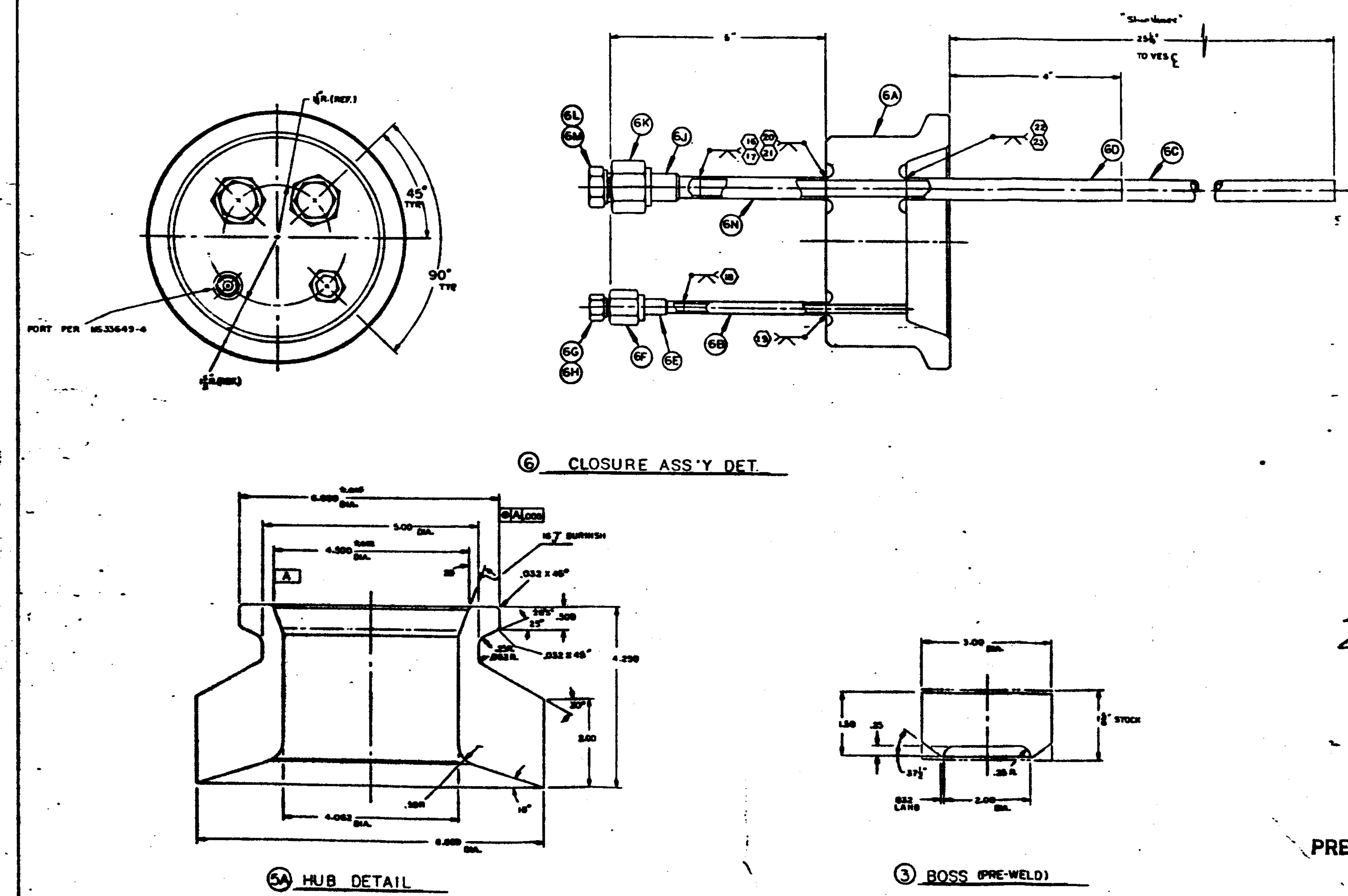

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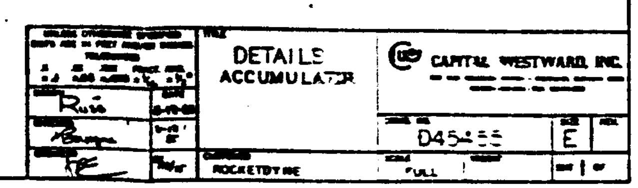

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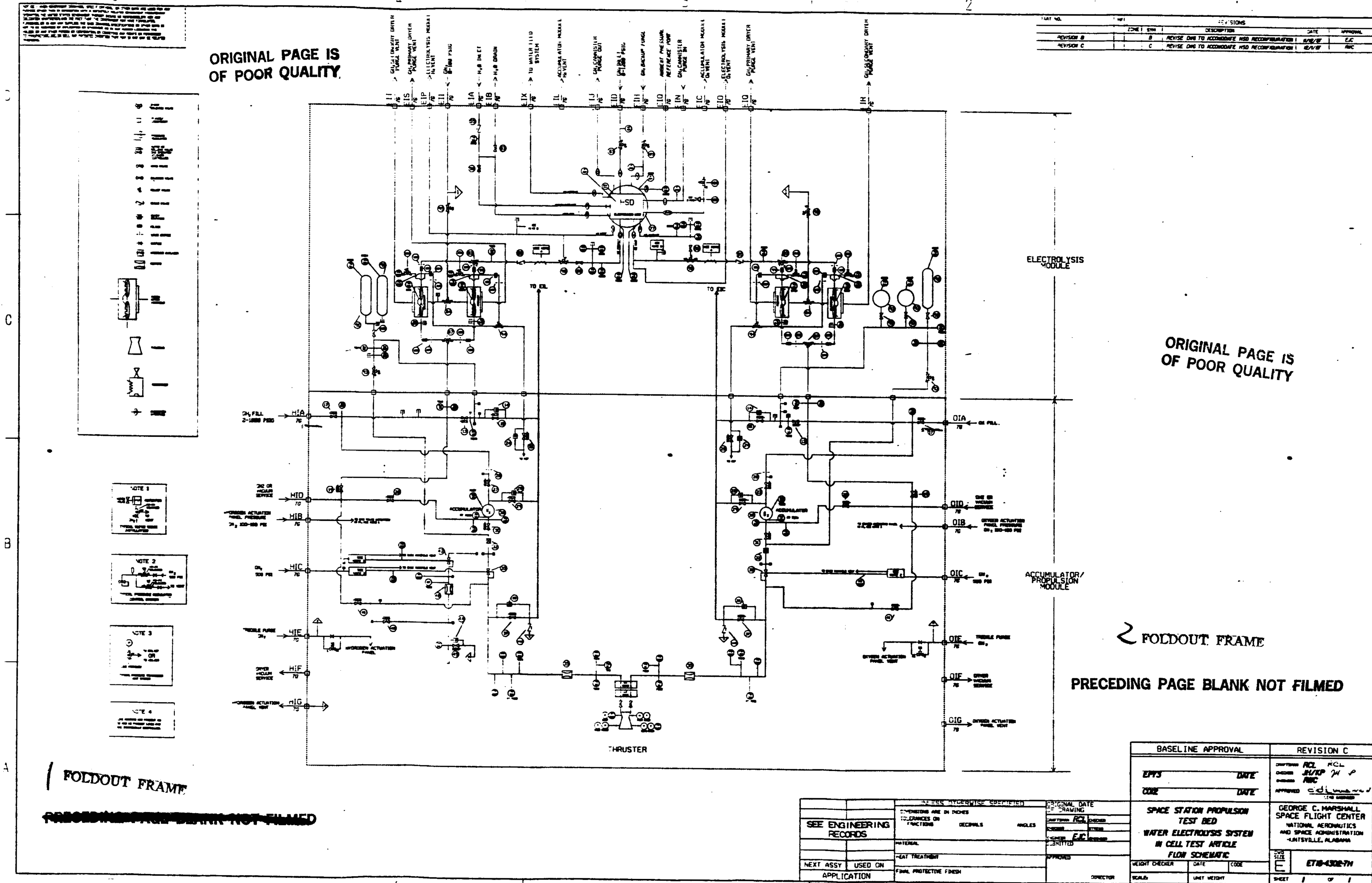
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ELECTROLYSIS MODULE
ACCUMULATOR/ PROPULSION MODULE
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ACCUMULATOR
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NOTE 2
NOTE 3
NOTE 4
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SPACE STATION PROPULSION TEST BED
WATER ELECTROLYSIS SYSTEM
IN CELL TEST ARTICLE
FLOW SCHEMATIC
GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA
ET8-4302-7H
SEE ENGINEERING RECORDS
NEXT ASSY
USED ON
APPLICATION
REVISIONS
REVISION B
REVISION C
REVISE DWG TO ACCOMODATE HSD RECONFIGURATION

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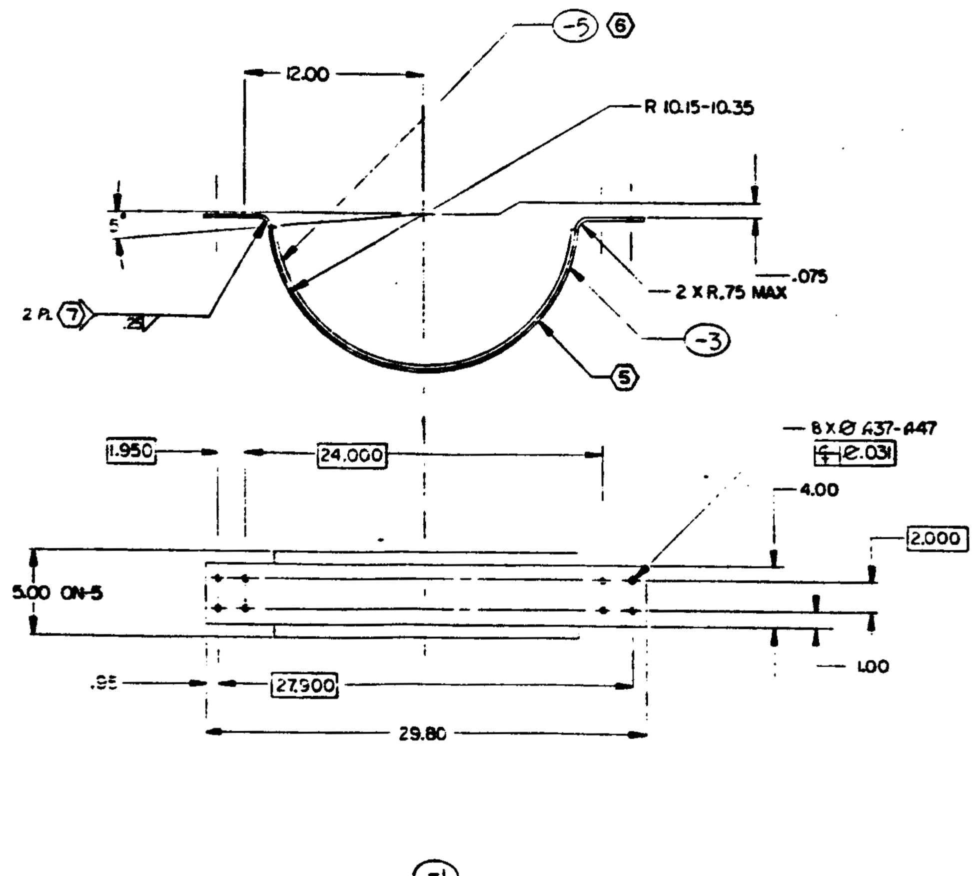

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7. ALTERNATE FABRICATION BY WELDING PERMISSABLE.
6. BOND WITH EASTMAN 910 PER ENGINEERING INSTRUCTION.
5. DEEP ELECTROCHEMICAL ETCH IDENTIFY PER RF0004-044 TYPE V.
4. CLEAN PER RA0110-025.
3. WELD PER RA0607-102 CLASS II.
2. MACHINE PER RA0103-016.
1. DRAWING INTERPRETATIONS PER RF0004-018.

NOTE UNLESS OTHERWISE SPECIFIED

	QTY	PART NO	DESCRIPTION	MATERIAL	SIZE	SPECIFICATION
	1	-5	PAD	BUTYL	.25 [illegible]	[illegible]
7	1	-3	CLAMP RING	6061-T4, T6 AL	.25 [illegible]	[illegible]
	-	7R032532	CLAMP ASSY			

HEAT TREAT	NONE
FINISH	NONE
MAT.	NOTED

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND APPLY PRIOR TO FINISH.

DO NOT SCALE PRINT

Rockwell International Corporation
Rocketdyne Division

M. F. CALLISON

E 02602

RI/RD89-104

Section A-2. This section contains all the drawings necessary for the assembly of the electrolysis module. The drawings are listed in Table A-2.

Table A-2. Electrolysis Module Drawings

ET16-4302-7H	MSFC Baseline Drawing for SSPTB Water Electrolysis System in Cell Test Article Flow Schematic
7R032840	Electrolysis Module Assembly
7R032825	Schematic Space Station Test Bed Electrolysis
7R032833	Schematic Space Station Test Bed Electrolysis/Resistojet
7R032836	Electrolysis Control Panel Assembly
7R032835	Propellant Control Panel Assembly
7R032832	Clamp Accumulator Mount Assembly
7R032831	Accumulator Mount Assembly
7R032830	Pallet, Assembly of Space Station Test Bed
7R032829	HSD Canister Assembly
7R032828	Electrolysis Unit Canister Assembly

SPACE STATION PROPULSION SYSTEM TEST BED - TEST LOG

NUMBER	DATE	INFORMATION	INJECTOR	CHAMBER	DURATION (sec)
P103-001	10/3/86	INERT GAS BLOWDOWN ACCEPTANCE TEST	N/A	N/A	550
P103-002	10/15/86	INERT GAS BLOWDOWN ACCEPTANCE TEST	N/A	N/A	550
P103-003	10/25/86	ACC TEST OF SSTPB PROPULSION MODULE	N/A	N/A	661
P103-004	12/03/86	INERT GAS BLOWDOWN ACCEPTANCE TEST	PROTOTYPE	PROTOTYPE	N/A
P103-005	12/03/86	N2/HE COLD FLOW TEST	"	"	N/A
P103-006	12/03/86	VERIFY IGNITION	"	"	1
P103-007	12/03/86	VERIFY IGNITION	"	"	5
P103-008	12/04/86	SYSTEM CHARACTERIZATION WITH TANK DURATION	"	"	291
P103-009	12/09/86	IGNITION SYSTEM CHECKOUT TESTS	"	"	0
P103-010	12/09/86	"	PROTOTYPE	PROTOTYPE	0
P103-011	12/09/86	"	"	"	0
P103-012	12/10/86	"	"	"	0
P103-013	12/10/86	IGNITION SYSTEM CHECKOUT TESTS	"	"	0
P103-014	12/10/86	"	"	"	0
P103-015	12/10/86	"	PROTOTYPE	PROTOTYPE	0
P103-016	03/11/87	"	"	"	N/A
P103-017	03/11/87	"	"	"	N/A
P103-018	03/12/87	"	"	"	1
P103-019	03/12/87	IGNITION SYSTEM CHECKOUT TESTS	"	"	5
P103-020	03/13/87	TANK DURATION; BURST DISK FAILED	PROTOTYPE	PROTOTYPE	0
P103-021	03/16/87	TANK DURATION; BURNED HOLE IN WATER DIFFUSER	"	"	60
P103-022	03/17/87	THRUSTER CHECKOUT TESTS	"	"	5
P103-023	03/17/87	"	"	"	5
P103-024	03/17/87	"	"	"	25
P103-025	07/20/87	"	PROTOTYPE	PROTOTYPE	10
P103-026	07/20/87	THRUSTER CHECKOUT TESTS	"	"	25
P103-027	07/20/87	INERT BLOWDOWN TEST	PROTOTYPE	PROTOTYPE	N/A
P103-028W	07/31/87	LSI ELECTROLYSIS TEST	N/A	N/A	68
P103-029	08/13/87	INERT BLOWDOWN TEST	PROTOTYPE	PROTOTYPE	N/A
P103-030	08/13/87	IGNITION/SEQUENCE CHECKOUT	"	"	120
P103-031	08/13/87	"	"	"	0
P103-032	08/13/87	"	"	"	0
P103-033	08/14/87	"	"	"	0
P103-034	08/14/87	IGNITION/SEQUENCE CHECKOUT	PROTOTYPE	PROTOTYPE	0

SPACE STATION PROPULSION SYSTEM TEST BED - TEST LOG

NUMBER	DATE	INFORMATION	INJECTOR	CHAMBER	DURATION (sec)
P103-035	08/14/87	IGNITION/SEQUENCE CHECKOUT	PROTOTYPE	PROTOTYPE	0
P103-036	08/19/87	"	"	"	120
P103-037	08/19/87	"	"	"	120
P103-038	08/19/87	IGNITION/SEQUENCE CHECKOUT	"	"	120
P103-039	08/20/87	IGNITION/SEQUENCE CHECKOUT; FAULTY CONTROLLER READOUTS	PROTOTYPE	PROTOTYPE	23
P103-040	08/20/87	IGNITION/SEQUENCE CHECKOUT; FAULTY CONTROLLER READOUTS	"	"	3
P103-041	08/26/87	IGNITION/SEQUENCE CHECKOUT	"	"	120
P103-042	08/26/87	IGNITION/SEQUENCE CHECKOUT; OX ACCUM LOW PRESSURE CUT	PROTOTYPE	PROTOTYPE	113
P103-043	09/01/87	INERT BLOWDOWN TEST	LeRC#1	LeRC#1	N/A
P103-044	09/01/87	INERT BLOWDOWN TEST	"	"	N/A
P103-045	09/01/87	INERT BLOWDOWN TEST	"	"	N/A
P103-046	09/01/87	LeRC THRUSTER EVALUATION; ALTERNATIVE IGNITION CHECKOUT	LeRC#1	LeRC#1	1
P103-047	09/02/87	"	"	"	0
P103-048	09/02/87	"	"	"	0
P103-049	09/02/87	LeRC THRUSTER EVALUATION; ALTERNATIVE IGNITION CHECKOUT	LeRC#1	LeRC#1	0
P103-050	09/11/87	"	"	"	0
P103-051	09/11/87	"	"	"	0
P103-052	09/15/87	"	"	"	5
P103-053	09/15/87	"	"	"	0
P103-054	09/15/87	LeRC THRUSTER EVALUATION; ALTERNATIVE IGNITION CHECKOUT	LeRC#1	LeRC#1	2
P103-055	09/15/87	"	"	"	0
P103-056	09/17/87	"	"	"	0
P103-057	09/17/87	"	"	"	10
P103-058	09/17/87	"	"	"	0
P103-059	09/17/87	LeRC THRUSTER EVALUATION; ALTERNATIVE IGNITION CHECKOUT	LeRC#1	LeRC#1	0
P103-060	09/29/87	"	"	"	0
P103-061	09/29/87	"	"	"	0
P103-062	09/29/87	"	"	"	0
P103-063	09/30/87	LeRC THRUSTER EVALUATION; ALTERNATIVE IGNITION CHECKOUT	LeRC#1	LeRC#1	minimum
P103-064	09/30/87	DRYER INERT BLOWDOWN TEST	N/A	N/A	N/A
P103-065	10/01/87	IGNITION SYSTEM EVALUATION	PROTOTYPE	PROTOTYPE	minimum
P103-066	10/08/87	IGNITION SYSTEM VERIFICATION	"	"	1
P103-067	10/08/87	"	"	"	1
P103-068	10/08/87	IGNITION SYSTEM VERIFICATION	PROTOTYPE	PROTOTYPE	1

SPACE STATION PROPULSION SYSTEM TEST BED - TEST LOG

NUMBER	DATE	INFORMATION	INJECTOR	CHAMBER	DURATION (sec)
P103-069	10/08/87	IGNITION SYSTEM VERIFICATION	"	"	1
P103-070	10/08/87	IGNITION SYSTEM VERIFICATION	PROTOTYPE	PROTOTYPE	1
P103-071	10/09/87	LeRC THRUSTER EVALUATION	LeRC#1	LeRC#1	10
P103-072	10/09/87	LeRC THRUSTER EVALUATION; TEMPERATURE REDLINE CUT	"	"	30
P103-073	10/09/87	LeRC THRUSTER EVALUATION; TEMPERATURE REDLINE CUT	"	"	30
P103-074	10/15/87	LeRC THRUSTER EVALUATION; TEMPERATURE REDLINE CUT	LeRC#1	LeRC#1	47
P103-075	10/22/87	WATER ELECTROLYSIS SYSTEM 1000 PSI LEAK CHECK	N/A	N/A	N/A
P103-076	10/26/87	INERT BLOWDOWN TEST	N/A	N/A	N/A
P103-077	10/26/87	INERT BLOWDOWN TEST	N/A	N/A	N/A
P103-078	10/27/87	THRUSTER CHECKOUT TEST	PROTOTYPE	PROTOTYPE	70
P103-079W	10/27/87	HSD WES TEST	N/A	N/A	0
P103-080W	10/31/87	"	N/A	N/A	0
P103-081W	11/00/87	"	N/A	N/A	0
P103-082W	11/13/87	"	N/A	N/A	0
P103-083W	11/14/87	"	N/A	N/A	0
P103-084W	11/16/87	HSD WES TEST	N/A	N/A	203hr
P103-085	Not used by DSU	FACILITY CHECKS			
P103-086	Not used by DSU	"			
P103-087	Not used by DSU	"			
P103-088	Not used by DSU	"			
P103-089	Not used by DSU	"			
P103-090	Not used by DSU	FACILITY CHECKS			
P103-091	12/01/87	HSD WES ACCUMULATED GAS	PROTOTYPE	PROTOTYPE	175
P103-092W	12/02/87	HSD WES FINAL SEQ	N/A	N/A	203hr
P103-093	12/16/87	INJECTOR EVALUATION	LHF, 40%	LeRC#1	2
P103-094	12/16/87	"	"	"	10
P103-095	12/16/87	"	"	"	30
P103-096	12/16/87	"	LHF, 40%	LeRC#1	120
P103-097	01/06/88	INJECTOR EVALUATION	LHF, 0%	LeRC#1	0
P103-098	01/06/88	"	"	"	0
P103-099	01/06/88	"	"	"	0
P103-100	01/12/88	"	"	"	2
P103-101	01/12/88	"	"	"	10
P103-102	01/13/88	INJECTOR EVALUATION	LHF, 0%	LeRC#1	15

SPACE STATION PROPULSION SYSTEM TEST BED - TEST LOG

NUMBER	DATE	INFORMATION	INJECTOR	CHAMBER	DURATION (sec)
P103-103	01/22/88	ADVANCE IGNITION EVALUATION	PROTOTYPE	PROTOTYPE	0
P103-104	01/22/88	"	"	"	0
P103-105	01/22/88	"	"	"	0
P103-106	01/22/88	"	PROTOTYPE	PROTOTYPE	0
P103-107	02/03/88	"	PROTOTYPE	SOLID NOZZLE	1
P103-108	02/03/88	ADVANCE IGNITION EVALUATION	"	"	1
P103-109	02/03/88	"	"	"	1
P103-110	02/03/88	"	"	"	0
P103-111	02/03/88	"	"	"	0
P103-112	02/03/88	ADVANCE IGNITION EVALUATION	PROTOTYPE	SOLID NOZZLE	1
P103-113	02/03/88	"	"	"	0
P103-114	02/03/88	"	"	"	1
P103-115	02/03/88	"	"	"	1
P103-116	02/03/88	"	"	"	1
P103-117	02/03/88	ADVANCE IGNITION EVALUATION	PROTOTYPE	SOLID NOZZLE	1
P103-118	02/03/88	"	"	"	0
P103-119	02/03/88	"	"	"	1
P103-120	02/03/88	"	"	"	1
P103-121	02/04/88	"	"	"	0
P103-122	02/04/88	ADVANCE IGNITION EVALUATION	PROTOTYPE	SOLID NOZZLE	0
P103-123	02/04/88	"	"	"	0
P103-124	02/04/88	"	"	"	1
P103-125	02/04/88	ADVANCE IGNITION EVALUATION	PROTOTYPE	SOLID NOZZLE	0
P103-126	02/17/88	LeRC THRUSTER EVALUATION	LeRC#1	LeRC#1	2
P103-127	02/17/88	"	"	"	10
P103-128	02/17/88	"	"	"	0
P103-129	02/17/88	"	"	"	28
P103-130	02/17/88	"	"	"	26
P103-131	02/17/88	"	"	"	0
P103-132	02/17/88	LeRC THRUSTER EVALUATION	LeRC#1	LeRC#1	0
P103-133	02/17/88	"	"	"	39
P103-134	02/17/88	"	"	"	32
P103-135	02/17/88	"	"	"	120
P103-136	02/17/88	LeRC THRUSTER EVALUATION	LeRC#1	LeRC#1	22

SPACE STATION PROPULSION SYSTEM TEST BED - TEST LOG

NUMBER	DATE	INFORMATION	INJECTOR	CHAMBER	DURATION (sec)
P103-137	02/17/88	LeRC THRUSTER EVALUATION	LeRC#1	LeRC#1	27
P103-138	02/17/88	"	"	"	29
P103-139	02/17/88	"	"	"	20
P103-140	02/17/88	"	"	"	24
P103-141	02/19/88	LeRC THRUSTER EVALUATION	LeRC#1	LeRC#1	28
P103-142	02/19/88	"	"	"	120
P103-143	02/19/88	"	"	"	120
P103-144	02/19/88	"	"	"	17
P103-145	02/19/88	"	"	"	120
P103-146	02/19/88	LeRC THRUSTER EVALUATION	LeRC#1	LeRC#1	17
P103-147	02/19/88	"	"	"	120
P103-148	02/19/88	"	"	"	45
P103-149	02/19/88	"	"	"	300
P103-150	02/22/88	"	"	"	300
P103-151	02/22/88	LeRC THRUSTER EVALUATION	LeRC#1	LeRC#1	300
P103-152	03/02/08	"	LeRC#2	LeRC#2	2
P103-153	03/02/88	"	"	"	10
P103-154	03/03/88	"	"	"	19
P103-155	03/03/88	"	"	"	17
P103-156	03/03/88	LeRC THRUSTER EVALUATION	LeRC#2	LeRC#2	18
P103-157	03/03/88		"	"	21
P103-158	03/03/88	"	"	"	24
P103-159	03/03/88	"	"	"	17
P103-160	03/03/88	"	"	"	120
P103-161	03/03/88	LeRC THRUSTER EVALUATION	LeRC#2	LeRC#2	120
P103-162	03/03/88	"	"	"	120
P103-163	03/03/88	"	"	"	120
P103-164	03/03/88	"	"	"	120
P103-165	03/03/88	"	"	"	0
P103-166	03/03/88	LeRC THRUSTER EVALUATION	LeRC#2	LeRC#2	36
P103-167	03/07/88	ADVANCED INJECTOR EVALUATION	LHF, 15%	LeRC#1	2
P103-168	03/07/88	"	"	"	10
P103-169	03/07/88	"	"	"	120
P103-170	03/07/88	ADVANCED INJECTOR EVALUATION	LHF, 15%	LeRC#1	97

SPACE STATION PROPULSION SYSTEM TEST BED - TEST LOG

NUMBER	DATE	INFORMATION	INJECTOR	CHAMBER	DURATION (sec)
P103-171	03/07/88	ADVANCED INJECTOR EVALUATION	"	"	120
P103-172	03/07/88	"	"	"	34
P103-173	03/07/88	"	"	"	120
P103-174	03/07/88	"	"	"	120
P103-175	03/07/88	ADVANCED INJECTOR EVALUATION	LHF, 15%	LeRC#1	120
P103-176	03/07/88	"	"	"	120
P103-177	03/07/88	"	"	"	120
P103-178	03/07/88	"	"	"	120
P103-179	03/07/88	ADVANCED INJECTOR EVALUATION	LHF, 15%	LeRC#1	82
P103-180	03/08/88	PROTOYPE PERFORMANCE VERIFICATION	PROTOTYPE	LeRC#2	35
P103-181	03/08/88	"	"	"	120
P103-182	03/08/88	"	"	"	0
P103-183	03/08/88	PROTOYPE PERFORMANCE VERIFICATION	PROTOTYPE	LeRC#2	0
P103-184	03/10/88	LeRC THRUSTER EVALUATION, INJECTOR ROTATED 135º	LeRC#2-135	LeRC#2	42
P103-185	03/10/88	"	"	"	38
P103-186	03/10/88	"	"	"	120
P103-187	03/10/88	"	"	"	120
P103-188	03/10/88	LeRC THRUSTER EVALUATION, INJECTOR ROTATED 135º	LeRC#2-135	LeRC#2	36

PROTOTYPE INJECTOR	ROCKETDYNE PROTOTYPE
PROTOTYPE CHAMBER	ROCKETDYNE PROTOTYPE
LeRC INJECTOR	NASA LeRC CANTRACT NAS-3-25142
LeRC CHAMBER	NASA LeRC CANTRACT NAS-3-25142
ADVANCED INJECTOR	ADVANCED DESIGN LOW HEAT FLUX INJECTOR
ADVANCED IGNITION	PROTOTYPE ACOUSTIC RESONANCE - NON ELECTRIC
WES	WATER ELECTROLYSIS UNIT
LSI	LIFE SYSTEMS, INC.
HSD	UNITED TECHNOLOGIES HAMILTON STANDARD
DSU	DATA SYSTEM UNIT
DG	DATA GENERAL

APPENDIX B

Space Station Propulsion Test Bed Test Summary

A total of 186 tests were conducted with the space station propulsion test bed from October 1986 through March 1988. The tests evaluated the test bed propulsion module (including the gas accumulator system), the water electrolysis system, the 25-lbf thruster, and ignition system. Advanced injector and ignition system designs were also tested. The integrated microprocessor computer controller was used throughout to command, control, and monitor all the tests.

A series of preacceptance, acceptance, and system evaluation tests were conducted on the test bed. The preacceptance tests consisted of checkouts and verifications of the system hardware and software elements. Upon completion of these tests, the system level acceptance tests were performed. Tests 001 through 003, conducted in October 1986, were the acceptance tests of the test bed propulsion module and consisted of blowdowns through the engine inlet lines to simulate firing a thruster and resistojet.

Tests 004 through 008 in December 1986 were the first tests of the prototype thruster on the system. These included blowdowns, ignition, and transition tests, and culminated with a 291 s system duration test. Tests 009 through 024 continued through March 1987 and explored the thruster operational characteristics and igniter variables. This also included a 5 s thruster firing (test 023) controlled from a remote terminal in California to demonstrate the flexibility and automation of the computer controlled system.

Tests 025 through 028 in July 1987 demonstrated the ability of the system to automatically produce the propellants using the LSI low-pressure WEU.

During August through October 1987 tests 029 through 074 were conducted in support of development of a 25-lbf thruster for NASA-LeRC at a mixture ratio of 8.

Tests 075 through 092 in October through December 1987 demonstrated the capability of the HSD 1,000 psi WEU system to produce propellants and fire the thruster on the propellants produced.

Beginning in December 1987 and continuing through March 1988, tests 093 through 188 were conducted in continued support of development of the 25-lbf thruster for NASA-LeRC and for advanced ignition and injector systems. A summary of the testing is contained in the following table.

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Section A-3. This section contains the thrust measurement system assembly drawing 7R034303.